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SOME ASPECTS OF THE ELECTRICAL TRANSMISSION OF POWER BY MEANS OF DIRECT CURRENT AT VERY HIGH VOLTAGES.

By H. RISSIK, B.Sc.(Eng.), Associate Member.

(*Paper first received* 23*rd March, and in revised form* 7*th December,* 1933; *read before* THE INSTITUTION 18*th January, before the* NORTH-WESTERN CENTRE 9*th January, before the* SOUTH MIDLAND CENTRE 15*th January, before the* NORTH-EASTERN CENTRE 22*nd January, before the* SCOTTISH CENTRE 23*rd January, before the* IRISH CENTRE 15*th February, before the* WEST WALES (SWANSEA) SUB-CENTRE 22*nd February, before the* EAST MIDLAND SUB-CENTRE 27*th February, before the* NORTH MIDLAND CENTRE 6*th March, before the* TEESIDE SUB-CENTRE 19*th March, and before the* HAMPSHIRE SUB-CENTRE 9*th May,* 1934.)

SUMMARY.

The difficulties and complication associated with the transmission of large blocks of electric power over considerable distances have led, during recent years, to a growing interest in the possible application of direct current at high voltage for this purpose. In spite of the fact that alternating current lends itself readily to generation and potential transformation in bulk, it cannot compete with direct current where transmission on a similar scale is concerned. For this reason direct current can, under certain circumstances, form an economic link between the source of energy supply and the consumer.

The paper presents a broad survey of the basic problems involved in generating, transmitting, and transforming electrical energy in the form of super-tension direct current as they appear at the present time, without attempting to add new matter to a subject which is of necessity highly specialized and the province of the transmission engineer.

After a brief historical review of the subject has been given in the Introduction, the manifold advantages of high-voltage direct current as a means of power transmission are discussed and the factors limiting its direct generation are investigated.

Of the several methods available for converting alternating current to direct current at high voltages, relatively few are at once technically and commercially feasible. A general account is given of those current-converting systems which seem to offer the most promising solution of the transmission problem.

The general trend of opinion in favour of the super-tension direct-current system as reflected in modern transmission projects is explained, and an outline is given of three such schemes of major importance which have been put forward during the last few years.

Finally, the paper indicates the course of a rational future development and suggests how the super-tension direct-current system of power transmission might with advantage be introduced and further technical data obtained.

References to recent literature dealing with the general transmission problem are given in a Bibliography.

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(1) HISTORICAL INTRODUCTION.

The discovery by Faraday, just over a century ago, of the principle of electromagnetic induction, must be considered the starting point in the evolution of electricity as a form of power. Previous to this, galvanic batteries had constituted the only available source of electrical energy. The introduction of electromagnetic machines driven by prime movers using either steam, gas, or water, as the working fluid, thus marked a considerable advance in the generation of electric power. It was not until 1866, however, when Siemens discovered the dynamo-electric principle and its application to the self-excitation of electrical machines, that the electricity supply industry began to develop along progressive lines.

The first power plants, operating on the constant-current system and employed chiefly for street lighting, were rapidly superseded by stations generating current at constant voltage, as this system of electricity supply presented considerable advantages. In the course of time large municipal power stations came to be erected containing many direct-current generators in parallel, and usually equipped also with large batteries of accumulators floating across the station busbars so as to ensure the most efficient utilization of the generators. When attention eventually came to be directed towards the supply of electricity to urban districts and beyond to the surrounding country, however, it was found that direct current was unsuitable for such a service owing to limitations imposed by low generation pressures and by the inability to effect potential transformation. Direct current therefore came to be displaced by alternating current, principally in the 3-phase form.

In the beginnings of power transmission during the 'eighties of last century, when polyphase alternating current was as yet unknown, not a few installations were built for transmitting direct current at high voltage. The first of these, connecting Munich and Miesbach, was built in 1882 by Deprez and Miller and operated at 2 000 volts. Several high-tension direct-current installations were erected by the eminent Swiss engineer Thury during the same period, of which the first large system was that built in 1887 to supply the industrial area centring round Genoa. The generators in the power station and the motors in the individual load centres were all connected in series. As a result of the success obtained with this installation a number of others were subsequently built. Amongst the most important of these transmission systems operating with high-voltage direct current and installed in this country may be mentioned that at Oxford, laid down in the early 'eighties, and that of the City and South London Railway, commenced in 1890 and subsequently extended and modified. A notable example of the series system was afforded by the 100-kV transmission in the western area of the Metropolitan Electric Supply Co.,* commissioned in March, 1911, and in operation until 1920, which employed underground cable to carry some 10 000 kW. As a later example of this system may be cited a multiple-unit winding installation in Ayrshire operating at 2 000 volts which was put into commission shortly before the War.

Thury gave an interesting account of such installations, and expressed his general opinion on the prospects of the direct-current system as developed by him, on the occasion of the 1930 Jubilee Celebrations of the Swiss Institution of Electrical Engineers.† The most important of these installations, and one which is still in operation to-day, is that transmitting power from Moutiers, in Savoy, to Lyons.‡ In 1906 the transmission line had a length of 225 miles and carried 75 amperes at 58 000 volts, corresponding to a transmitted power of 4 350 kW. By 1930 the transmission distance had extended to 280 miles, including some 50 miles of underground high-tension cable, the current carried had increased to 150 amperes, and the transmission voltage to 125 000 volts, corresponding to a transmitted power of 18 750 kW. This is by no means an inconsiderable achievement, even if it does not quite bear comparison with modern alternating-current transmission practice.

Generally speaking, this installation and the power transmission system of which it is such a remarkable example have been accorded little attention in the past, the transmission engineer having devoted his entire studies to the transport of electric power by means of high-tension alternating current. Without doubt this is attributable to the rapid development in recent years of a transmission technique which has made it possible—at any rate technically, if not commercially—to transmit any amount of power over any conceivable distance on this earth by means of 3-phase alternating current. Nevertheless the transmission of power by means of direct current at high voltage would seem to be a more simple and less costly process, enabling the expensive compensating stations and terminal switchgear essential to alternating-current transmission to be dispensed with. The main reason why direct current has been seriously neglected by the transmission engineer, however, is that only lately has apparatus other than rotating plant been available for converting current from the alternating to the direct form and vice versa. The losses associated with conventional rotating plant were such as to hinder the development of direct-current transmission. A more favourable aspect was given to the problem, however, by the advent of the synchronous commutator convertor, the so-called transvertor of Calverley and Highfield, in 1924; and still further attention has been devoted to the possible utilization of direct current for the transmission of electric power since the successful development of the grid-controlled steel-tank mercury-arc rectifier, details of which were first published in this country in an article by the author which appeared in the *Electrical Review** nearly three years ago. Finally, it is interesting to note the experiments of Marx in connection with the valve action of a high-voltage electric arc in air, which culminated in the construction of a heavy-duty power-arc rectifier.† All such new developments in the technique of arc rectification go to indicate that a practical solution to the problem of high-tension direct-current transmission will be found in the not far-distant future.

(2) COMPARISON BETWEEN DIRECT-CURRENT AND ALTERNATING-CURRENT POWER TRANSMISSION.

Since Dolivo-Dobrowolski gave his classic exposition of the limits of alternating-current power transmission‡ much has been written on the subject of the advantages of direct current for transmitting electrical energy on a large scale.§ The fact that this question has been dealt with so often and has been treated so thoroughly in the past, notwithstanding the absence of economic methods of generating and converting direct current at high voltages, is in itself an indication of the importance which attaches to the problem.

All investigators are agreed that in theory the transmission of large blocks of power over great distances can be effected more cheaply with direct current than with 3-phase alternating current, but differences of opinion arise as to the minimum power and distance at which the direct-current system still has the advantage. Before discussing this particular aspect of the problem it is perhaps convenient to summarize briefly the main differences between the direct-current and the 3-phase alternating-current systems of power transmission.

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* *Journal I.E.E.*, 1912, vol. 49, p. 848.

† *Bulletin Schweizerischer Elektrotechnischer Verein*, 1930, vol. 21, p. 159.

‡ *Elektrotechnische Zeitschrift*, 1906, vol. 27, p. 1091.

* See Bibliography, (11).

† E. MARX: "Arc Rectifiers" (Julius Springer, 1932).

‡ *Elektrotechnische Zeitschrift*, 1919, vol. 40, pp. 1 and 84.

§ See Bibliography, (1), (2), (5), (6), (8), (12), (13), (14), (15), (17), and (22).

(i) *Voltage Regulation.*

In the case of direct current, the voltage-drop due to inductance and the voltage-rise due to capacitance are absent, and hence no equipment is required for compensating the reactive kVA of the transmission line.

(ii) *Current Density.*

Direct current distributes itself uniformly over the cross-section of the conductor, which is thus utilized to the full, whilst alternating current tends to gravitate away from the centre of the cross-section. In other words, the skin effect which is characteristic of alternating current at high voltages is absent in the case of direct current.

(iii) *Corona.*

The corona loss with direct current is considerably less, as the critical voltage is 41 per cent higher than for alternating current. Furthermore, such losses are dependent on frequency. For the same voltage values the corona loss with direct current amounts only to some 60 to 70 per cent of that with alternating current.

(iv) *Insulation.*

A double-circuit 3-phase alternating-current transmission line insulated for a voltage of, say, 132 kV, can be utilized as a triple-circuit direct-current line, with earthed neutral, operating at 370 kV between positive and negative. Under these conditions the same power can be transmitted with a line loss amounting to less than one-sixth of that occurring with alternating-current transmission.

(v) *Cables.*

As in direct-current transmission no dielectric losses occur, and insulating materials can thus be stressed many times more severely than with alternating current, cables can be used even at very high d.c. voltages. The present technique of cable manufacture will permit of cables being constructed to carry direct current at a potential of 300 kV to earth, i.e. 600 kV between positive and negative conductors. As for equal outputs it would appear that a high-tension direct-current cable is no more costly than an overhead line,* there seems to be no reason why such cables should not be employed to transmit large powers over great distances, especially where wide river and sea crossings have to be made.

(vi) *Stability.*

In direct-current operation the stability of the transmission system is only influenced by the ohmic resistance of the line. The question of voltage-vector displacement at both ends of the line, and therewith of the system falling out of step, does not arise. In an alternating-current transmission system all synchronous machines running in parallel are bound to the same frequency. Consequently there is always the danger of different power stations falling out of synchronism in the event of short-circuits or of sudden changes of load. Furthermore, where power is transmitted over very great distances by means of alternating current it is necessary to introduce phase-compensating stations at intervals throughout the line if stability of the transmission system is to be assured.

(vii) *Reactive Power.*

The capacitance current of the line is absent when power is being transmitted by direct current. For a single-circuit 3-phase alternating-current 100-mile transmission line with a conductor cross-section of 0·15 sq. in., the amounts of wattless power necessary to deal with the charging current in various cases are approximately as follows: (*a*) 60-kV overhead line, 1 600 kVAR; (*b*) 100-kV overhead line, 4 500 kVAR; (*c*) 60-kV cable, 28 750 kVAR; (*d*) 100-kV cable, 64 000 kVAR.

From the foregoing it is apparent that the numerous advantages in favour of direct current are only realized to their fullest extent where the amount of power to be transmitted is considerable and the transmission distance great. The many factors which have to be taken into consideration render it impossible to state at what value of power and distance direct-current transmission becomes more economical than alternating-current transmission. A very interesting investigation of the problem has, however, been made by Piloty,* who has developed certain general expressions from which it is possible to gain some idea of the comparative costs of the two systems of power transmission. From the formulæ given by him it is also possible to establish a numerical comparison for given operating conditions and certain assumed cost figures. Broadly speaking, the direct-current system is the more economical for transmission distances exceeding 100 miles and/or for powers above 100 MW.

When considering the merits of high-tension direct current as a power-transmitting medium in the light of the foregoing general observations it must not be forgotten that a number of problems, essentially of a practical nature, will inevitably arise when the first attempt is made to operate such a transmission system. Means must be devised for maintaining the voltage of the system and for suppressing any harmonic ripple which would otherwise be carried by the transmission line. Again, reliable indicating and metering equipment will have to be provided on the direct-current side, whilst adequate precautions will have to be taken to protect the system from lightning surges and other transient disturbances. It seems probable also that means will have to be provided for dissipating the static charge held by the transmission line; this could probably be effected without difficulty by the converting equipment. Questions of insulation and earthing, as well as of possible electrolytic effects, will also require careful consideration.

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* H. Glaser [see Bibliography, (12)] points out that the price-ratio for a.c. cables and overhead lines operating at 110 kV is in the region of 2½ : 1. Taking a more conservative estimate of this price-ratio, viz. 4 : 1, or even 6 : 1, in the case of higher voltages, and bearing in mind that a d.c. line can carry at least 4 times, and, under certain conditions, over 6 times the amount of power that can be transmitted over an equivalent a.c. line, there seems to be no reason why d.c. transmission by cables would not be an economic proposition.

* See Bibliography, (15).

Finally, there is the problem arising from the inability of a direct-current transmission line to carry reactive power. This fundamental question will in all probability have an important bearing on the general utility of the direct-current system as a solution to future transmission problems.

(3) The Generation of Super-Tension Direct Current.

In discussing the relative merits of the two basic systems of power transmission it has been assumed that means are available for obtaining electrical energy in the form of direct current at high voltage. The direct-current transmission installations which have so far been built all operate on the series system, in which a constant current is generated directly at a variable voltage. In spite of the very valuable experience gained by the erection and operation of such installations, and notwithstanding the indefatigable zeal and energy with which Thury has continued to develop and to perfect this system in the face of difficulties offering the maximum obstruction to the pioneer, it seems doubtful whether the series system can ever attain to universal application. The limits to the Thury system are twofold. In the first place, it is extremely difficult to construct direct-current machines for high voltages and large outputs (i.e. of the order of tens of thousands of kilowatts) with any degree of security. Secondly, as the transmission losses are constant, the efficiency falls off very rapidly with decreasing load. In recent years, however, Thury has developed means for regulating the current output within certain limits, and the latter disadvantage has therefore to a very large extent been overcome.

The largest constant-current generators so far built are some of those supplying the Moutiers–Lyons system, which have three commutators in series and deliver 150 amperes at 22 kV. Thury himself envisages tandem turbo-generator sets of 16 000 kW capacity, each generating unit giving an output of 400 amperes at 20 kV from a double commutator.

It must, however, be borne in mind that such generators are expensive to construct, as they are essentially low-speed machines. A little consideration of the voltage formula $V = ev_c/(2fs)$, where e is the mean voltage between adjacent commutator segments, v_c is the peripheral speed of the commutator in metres per sec., f is the frequency, s is the pitch of the commutator segments in millimetres, and V is the terminal voltage in kV, shows that to attain even 10 000 volts per commutator it is already necessary to push the values of e, v_c, and s to the utmost limits. For example, with $e = 25$, $v_c = 40$, and $s = 5$, a frequency as low as 10 cycles per sec. is arrived at; and for a 4-pole machine this corresponds to a speed of 300 r.p.m. By reducing the segment pitch to 4 mm this speed could be increased to 375 r.p.m. or, alternatively, the commutator voltage could be raised to 12 500 volts.

In order to determine the maximum output obtainable from a direct-current generator under these conditions it is necessary to consider the output formula $P = 3qev_a/n$, where q is the specific electric loading, v_a is the peripheral speed of the armature in metres per sec., n is the speed of the machine in r.p.m., and P is the output in kW. Taking the limiting values, $q = 550$, $e = 25$, and $v_a = 58$, the maximum output of the 300-r.p.m. machine would be 8 000 kW, or 800 amperes. Triple-unit double-commutator generators of this type could thus be designed to give an output of 48 000 kW at 60 kV, or, possibly, 60 000 kW at 75 kV. By connecting 8 such sets in series, transmission voltages of 480 kV or 600 kV could therefore be attained, the power-transmitting capacity being of the order of 400 to 500 MW. Such figures compare favourably with those put forward in connection with the Norway–Germany power-transmission project or the San José scheme. At the same time they must be regarded as representing the utmost limits of the Thury system.

(4) Practicable Current-Converting Systems.

It is evident that such machines cannot compete with modern steam or water turbine-driven alternators. If direct-current transmission is to be the basis either of a tangible reduction in the cost of transmitting electrical energy or of an increase in the distances over which such energy can be economically transmitted, then it is essential that means be found for generating alternating current in large high-speed machines, as has been done hitherto, and for converting it to direct current in relatively few units of apparatus independent of the form of current. It is furthermore equally important that similar means be found for transforming the high-tension direct current back again into 3-phase alternating current at constant voltage. A prerequisite to success in this direction is that the armature windings should not rotate, but should remain stationary as in the ordinary transformer.

(*a*) *Synchronous Commutator Rectifiers.**

Of all the forms of mechanical rectifying devices the synchronous commutator rectifier has perhaps been given the least attention, at any rate from the point of view of providing direct current at high voltages. Since Hutin and Leblanc tried out their *panchahuteur* at the beginning of this century, however, various forms of commutator rectifiers have been developed. Kesselring† has investigated the possibilities of rotating jets for rectifying high-tension alternating current after the manner of the rotary-jet rectifier of Latour.‡ He considers that such rectifiers can be constructed to give 40 kV per jet and 1 000 amperes direct current with a full-load loss of only 0·5 per cent, but no experience has been gained in this direction up to the present.

By far the most important advance in the mechanical conversion of current at high voltage is represented by the transvertor invented by Calverley and Highfield, which may be regarded as a combination of static transformer and rotary convertor having a stationary armature and rotating brush-gear. The development of this apparatus (sponsored by the English Electric Co.) culminated some years ago in the construction of a 2 000-kW unit for converting 3-phase alternating current at 6 600 volts to direct current at 100 000 volts.§ The transvertor is essentially a static current convertor, and it has the further merit of being completely reversible. As is well known, the conversion of alternating current to direct current involves the following three distinct functions: (1) voltage transformation, (2) phase multiplication, and (3) commutation. Of these, the first provides the required adjustment of voltage, whilst the second ensures constancy of the unidirectional voltage furnished by the third operation. In the conventional transformer and rotary-convertor combination, phase multiplication is effected chiefly in the armature of the convertor. In the transvertor, on the other hand, both voltage transformation and phase multiplication are carried out in a static piece of apparatus comprising several polyphase transformers grouped together, from which connections are taken to stationary commutators. The only moving part of the apparatus is thus the rotating brush-gear driven by a relatively small synchronous motor. Over-excitation of this motor enables it to supply the magnetizing current of the transformer element, and owing to the arrangement of its stator winding it is able to provide, through appropriate tappings, the several phase-displaced voltages necessary for complete compensation of the transformer element of the machine.* The arrangement ensures good commutation of the transvertor under all possible conditions of loading, a rectified voltage practically free from ripple, and a sinusoidal-input current at all loads.

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* L. B. W. Jolley: "Alternating Current Rectification," chap. 5 (3rd ed., Chapman and Hall, 1928).

† *Verband Deutscher Elektrotechniker Fachberichte*, 1931, p. 21.

‡ *Revue Générale d'Électricité*, 1926, vol. 19, p. 893.

§ See Bibliography, (3).

The overall efficiency of the unit just referred to attained to 96 per cent between full load and about ½ load, and fell to only 93 per cent at ¼ load. This high efficiency over such a wide range of load is attributable to the low iron and copper losses which can be achieved in apparatus of this class, as well as to the small losses occurring in the rotating parts. Naturally, with much larger units the efficiency can be increased even further. High and constant efficiency is of paramount importance in voltage transformation and current conversion. Furthermore, the efficient transmission of electrical energy by means of direct current necessitates a constant high voltage. These two reasons alone make it clear that serious consideration ought to be given to the transvertor, which affords a rational solution to the transmission problem.

(b) *Vapour-Arc Discharge Devices.*

Probably the main reason why in past years direct current was not more seriously considered for power transmission was that suitable apparatus for current conversion by static and non-mechanical means was not available, whilst the direct generation of high-tension direct current was regarded with disfavour. It is undoubtedly due to the successful development of vapour-arc discharge devices in a form suitable for heavy-duty service that interest has been reawakened in the possibility of transmitting power by means of direct current.†

The only existing types of vapour-arc discharge devices suitable for current conversion at high voltage are the mercury-arc rectifier and the hot-cathode rectifier. Both function with mercury vapour and consequently with a low arc voltage-drop, but the former relies on cathode-spot electron emission whilst the latter depends on thermionic emission. The mercury-arc rectifier is already well known by virtue of its extensive application to the supply of direct-current traction systems, in which field it is rapidly displacing the rotary convertor. There is, in fact, every indication that the mercury-arc rectifier is becoming the standard form of apparatus for converting alternating current to direct current, except, perhaps, in the case of very low operating voltages. Mercury-arc rectifiers have been built for outputs of 16 000 amperes and for working voltages up to 30 kV. Hot-cathode rectifiers (with a single anode) have been constructed for outputs of 400 kW at 40 kV, whilst cathodes capable of emitting 1 000 amperes appear to have been successfully manufactured. The special cathode construction employed is such that the sponsors of the hot-cathode rectifier development claim current ratings of 10 000 amperes as possible.

Both the foregoing types of vapour-arc discharge devices are capable of inverting direct current to alternating current if provision is made for a suitable control of the potential applied to grids interposed between the several anodes and the cathode. The development of the grid-controlled mercury-arc rectifier and of its hot-cathode counterpart, the thyratron, has besides opened up a large number of new spheres of application* which had previously been closed to such static apparatus. It would appear, however, that the real future of the grid-controlled rectifier, whether of the mercury-arc or of the hot-cathode type, lies in its ability to invert direct current to alternating current, and in the solution which it thus affords of the transmission problem. This future is, of course, intimately bound up with the question of obtaining high output voltages from rectifiers of any size. At present it seems unlikely that a 10 000-kW unit of the mercury-arc type could be made to operate reliably at voltages above 20 to 30 kV, and as regards hot-cathode rectifiers no experience has as yet been gained with large units necessitating a steel-tank construction. Whether these limits will be exceeded in the near future is a question which can only be decided as the outcome of further research and technical development.

(c) *Atmospheric-Arc Valves.*

The difficulty in constructing vapour-arc valves for high voltages and, at the same time, high current outputs, lies mainly in that the two requirements are contradictory. A mercury-arc rectifier specially constructed to carry heavy currents is not readily adapted to withstand a high reverse voltage during the impermeable half-cycle. Conversely, a high-tension thyratron, for example, is quite unsuitable for handling large currents.

As is well known, the reverse voltage in a power arc between electrodes in air can be made to attain a very much higher value than in the case of arc discharges in valves operating with vapour at pressures of the order of thousandths of a millimetre of mercury column. Moreover, it has been established that the breakdown voltage of a discharge path in air, and therewith the reverse voltage obtainable by means of any electric valve employing an arc discharge in air, increases with the air pressure up to about 25 atmospheres. Marx has made use of this property in investigating the possibilities of obtaining a valve action from the arc discharge between electrodes in air, and in collaboration with his staff and students at the Braunschweig Technical College he has recently conducted an extensive inquiry into the operating characteristics of various designs of atmospheric-arc valves.* Subsequent experiments have demonstrated that such atmospheric-arc valves can be constructed so as to carry 250 amperes during the permeable half-cycle and to withstand 400 kV in the impermeable half-cycle of anode voltage.

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* See Bibliography,(3); also R. T. Smith: *Journal I.E.E.*, 1931, vol. 69, p. 964.

† See Bibliography, (11), (20), and (25).

* *Engineering*, 1932, vol. 134, p. 564; also *Engineer*, 1932, vol. 154, p. 487.

(5) DIRECT-CURRENT TRANSMISSION PROJECTS.

A study of the *Transactions* of the Second World Power Conference held in Berlin in the summer of 1930 not only reveals the intense interest which is being taken nowadays in the transmission of electrical energy, but also indicates the general trend toward the use of super-tension direct current for the purpose. The transmission engineer of to-day thinks of powers and distances in terms that render alternating current uneconomic, if not quite unsuitable, for electrical transmission.

An immediate outcome of this changed outlook has been the serious consideration given to super-tension direct current in the planning of national and international schemes for transmitting large blocks of electric power. The three "north-south" and the two "east-west" transmission lines of the European super-power grid system (Fig. 1) discussed at the 1930 Conference* already cover a distance of nearly 7 000 miles. By abandoning 3-phase alternating current at 400 kV, as originally proposed, in favour of direct current at 500 kV, a very considerable financial saving would be effected. Amongst other super-power transmission schemes put forward of late years may be mentioned the transfer of energy to the extent of 5 000 million kWh annually from the western fjords of Norway to the industrial areas in Westphalia, the plan for harnessing the tides in the San José Gulf and transmitting nearly 3 million kW over a distance of some 700 miles to Buenos Aires, and the electrification of Egypt and the Nile Delta from the water-power resources of the great dam at Assuan.

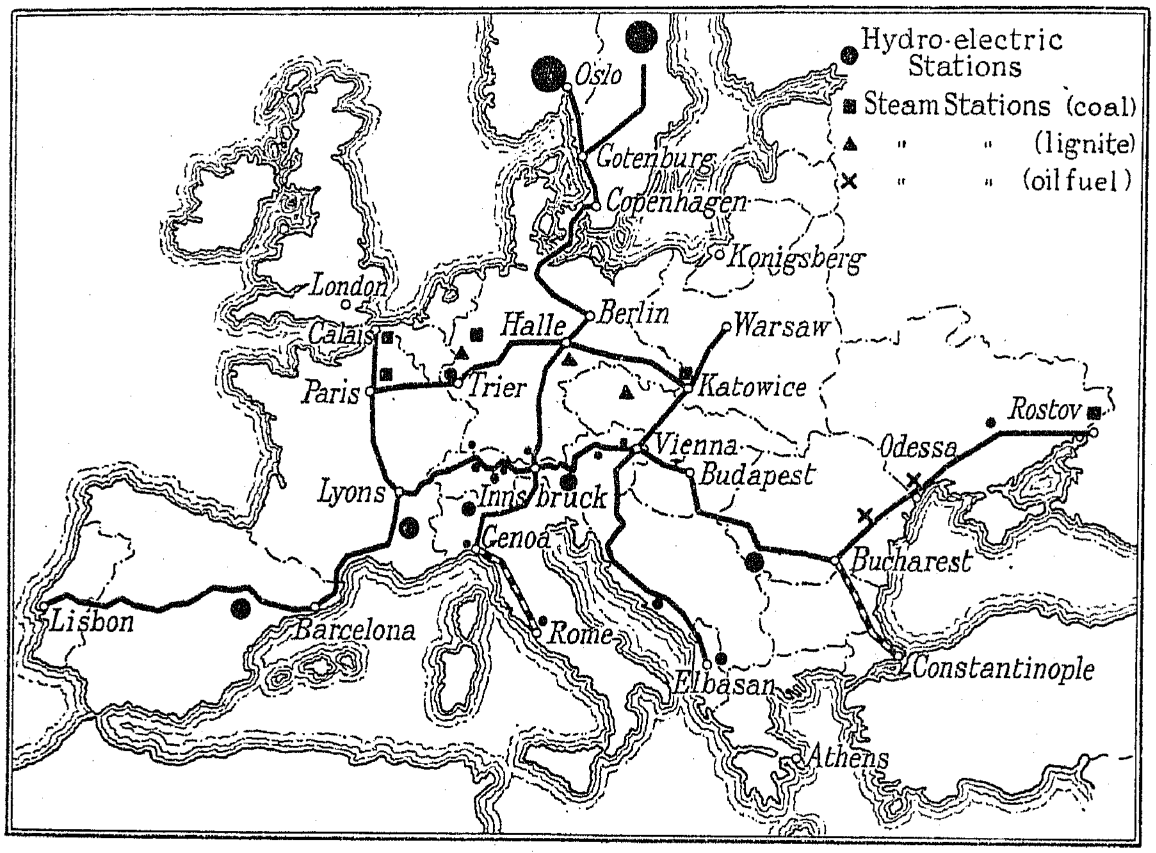

FIG. 1.—Proposed European 400-kV super-power grid system.

(a) *The Norway–Germany Transmission Line.*

Of the above power-transmission projects none has perhaps given rise to so much technical discussion as the plan for transmitting nearly 1 million kW from Norway, through Sweden and Denmark, to Germany. This scheme (Fig. 2) is particularly interesting in that it involves several sea crossings varying in width from 3 to 12 miles and amounting to 23 miles in all. The water-power resources of the fjords on the western coast of Norway have the characteristic advantage of being able to deliver their maximum output all the year round, owing to the equalizing influence of the Gulf Stream. Tremendous quantities of water are available at very high heads, and it is estimated that several such fjords have a potential output of $1\frac{3}{4}$ million kW. The scheme provides for a hydro-electric station of 1 250 MW installed capacity situated on one of these fjords, and a transmission line to Hamburg via Dalem, Drammensfjord, Landesgrenze, Göteborg, and Copenhagen. Of the 950 MW exported, 100 MW would be tapped off at Göteborg for Sweden, 100 MW at Copenhagen for Denmark, whilst the remaining 750 MW would be transformed down at Hamburg for distribution by the Rheinisch-Westfaelisches Elektrizitaetswerk supply system.

Gosebruch has estimated* the capital cost of this undertaking, and the unit cost of the electrical energy distributed, for the following cases.

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* See Bibliography, (10), (23), and (24).

† *Ibid.*, (7), (9), and (21).

* See Bibliography, (14).

(i) Alternating-current generation at 10 kV, 3-phase, 50 cycles per sec., and transmission at 400 kV with 6 phase-compensating stations. Power would be generated by 16 Pelton turbo-alternator sets of 80 000 kW capacity and would be transmitted throughout by a double-circuit overhead line equipped with hollow copper conductors having a diameter of 2 in. and a cross-section of 0·8 sq. in.

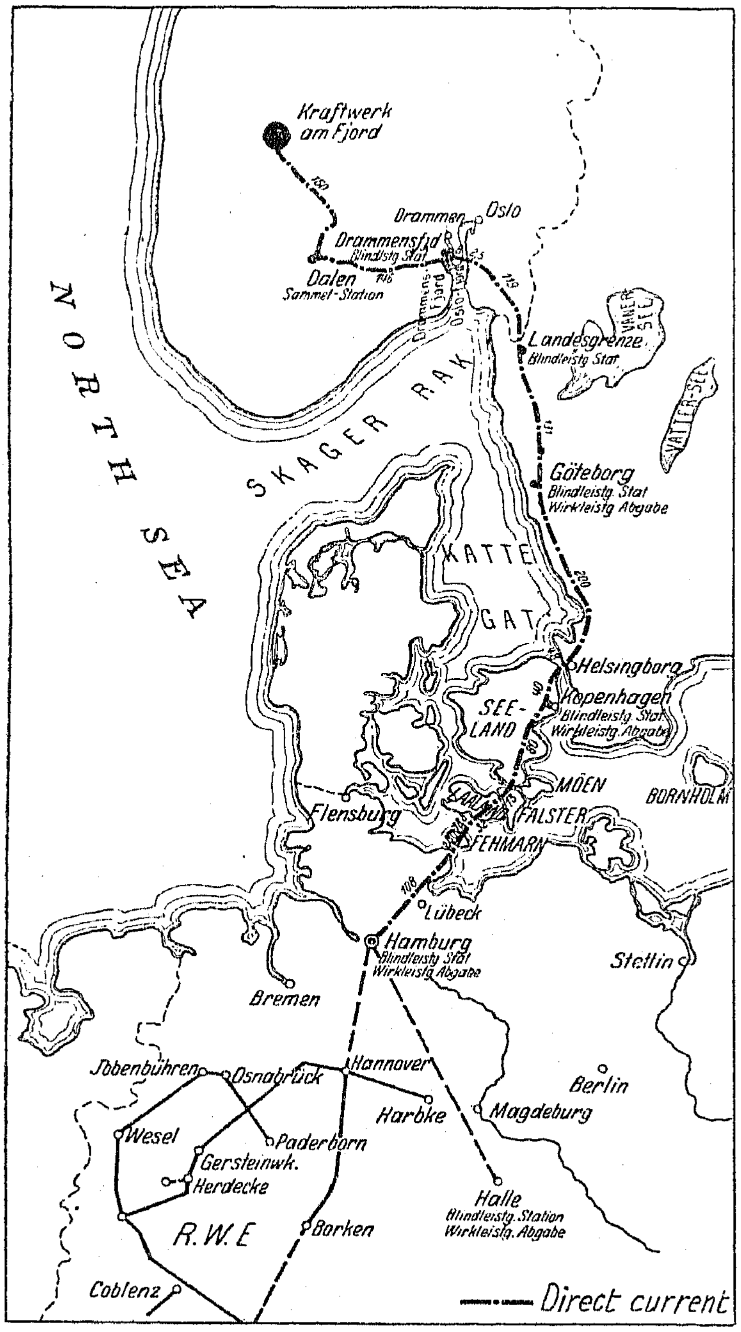

Fig. 2.—Norway–Germany transmission project.

(ii) Direct-current series (Thury) system with 128 constant-current generator sets in the power station, each set delivering 3 200 amperes at 3 125 volts. Turbines would be coupled to groups of 4 generators in series to give an output per group of 40 000 kW at 12 500 volts. Transmission would be at 400 kV by means of a double-circuit overhead line and two earthed (neutral) lines equipped with solid copper conductors having cross-sections of 0·78 and 0·15 sq. in. respectively. Water crossings would be carried out with 200-kV armoured cable. The distributing stations at Göteborg and Copenhagen would each contain 3 motor-generator sets of 40 000 kW capacity and consisting of 4 motors in series coupled to a 10-kV generator, whilst the station at Hamburg would be equipped with 11 such motor-generator sets of 80 000 kW capacity.

(iii) Alternating-current generation as in (i), and direct-current transmission as in (ii), employing mercury-arc rectifiers in the power station and motor-generator sets in the distributing stations.

(iv) Same as (iii), but with mercury-arc invertors in the distributing stations.

The results of his investigations are given in the Table. It is seen that scheme (iv) provides a saving of 5 per cent as compared with scheme (i), representing a saving in capital outlay amounting to £2 350 000 together with an annual saving of £250 000.

(*b*) *The San José Tidal Power Project.*

From time immemorial it has been recognized that the tides represent a source of energy as inexhaustible as it is inevitable. Of recent years several eminently practical schemes have been put forward for making use of this hitherto unexplored source and converting the energy to industrial purposes. Of these, the San José hydro-electric project is by far the largest and most important. It provides for the exploitation of the tidal energy available in the Gulf of San José on the Patagonian coast, and represented by from 20 to 35 million gallons per sec. at a head varying from 20 to 90 in., in 375 turbo-generator sets having a total daily output of 10 million kWh. The capital cost of this tremendous

Table.

Scheme	Generation		Transmission and distribution		Total		Percentage
	£ millions	Pence per kWh	£ millions	Pence per kWh	£ millions	Pence per kWh	
(i)	30·80	0·149	17·15	0·084	47·95	0·233	100
(ii)	32·20	0·155	17·25	0·086	49·45	0·241	103
(iii)	30·85	0·150	17·25	0·086	48·10	0·236	101
(iv)	30·85	0·150	14·75	0·073	45·60	0·223	95

undertaking has been estimated at £20 millions. In view of the fluctuating and very low head the turbines have to operate over a wide speed-range. Alternating-current generators cannot be coupled to low-pressure turbines working under such conditions except through complicated gearing, which is both costly and inefficient. On the other hand direct-current generators can be driven at speeds fluctuating between wide limits, especially if the machines are of the constant-current type in which the terminal voltage is reduced according to the fall in speed. For this reason tidal-power stations are more favourable to the generation of direct current than of alternating current. In the San José scheme each turbine would be direct-coupled to a constant-current generator delivering 5 000 amperes at 1 600 volts, corresponding to an output of 8 000 kW. All the generators would be connected in series to give a total output of 3 million kW at 600 kV, which would be transmitted to Buenos Aires by a 700-mile double-circuit line with earthed neutral. It is estimated that the cost of electrical energy delivered at Buenos Aires would be not more than ⅛d. per kWh.

(*c*) *The Assuan Hydro-Electric Scheme.*

The object of this scheme is to utilize the potential energy of the water stored behind the great dam at Assuan for the electrification of Egypt, the Nile Delta, the industrial area centring round Cairo, and, in particular, certain proposed synthetic (nitrogenous) fertilizer plants. The maximum available head at the moment is 85 ft., and this would eventually be increased to 115 ft. on completion of the extensions to the dam. The minimum head is 10 ft.; it occurs in summer and with open sluice gates. The problem consists in making the fullest possible use of the water power available under these circumstances. None of the three solutions put forward involving constant-speed turbines and alternating-current generators was found acceptable. A solution was, however, afforded by the use of direct-current generators operating at variable speed on the Thury system. It is proposed to transmit 120 MW by means of direct current at 300 kV, employing for this purpose the existing 220-kV transmission line to Cairo, some 550 miles long. Power would be generated by 15 turbo-generator sets giving an output of 400 amperes at 20 000 volts, each generator having four 5 000-volt commutators in series.

(6) THE DIRECTION OF FUTURE DEVELOPMENT.

Analysis of the direct-current transmission problem indicates that, up to the present, the difficulties have resided in the efficient conversion of current on a large scale and at high voltage; the advantages lie in the transmission line.

The possible gain in transmitted power capacity which can be realized by changing over an existing and overloaded alternating-current transmission line to direct-current operation is unfortunately seldom appreciated. Consider, for example, a double-circuit 3-phase line of steel-cored aluminium conductor having an equivalent copper cross-section of 0·175 sq. in., a length of 100 miles, and operating at 132 kV. Taking an economic current density under these conditions of about 1 100 amperes per sq. in. for copper, the carrying capacity of each line would be 195 amperes, or 44 500 kVA. At a power factor of 0·9 the power transmitted would be 40 000 kW, or 80 000 kW for the double-circuit line. The losses per line would amount to 2 880 kW, or 7·2 per cent. On changing one line over to direct-current working the insulation would be sufficient for at least 185 kV; so that the line could be operated on the 3-wire system with an earthed neutral and 370 kV between positive and negative conductors. The power transmitted would then be 72 000 kW, and the line losses 1 920 kW, or 2·7 per cent. With such a low loss the equivalent current loading might with safety be raised to some 2 400 amperes per sq. in., and the carrying capacity of the line would thus be increased to 160 000 kW, i.e. 4 times that of the alternating-current line. The line losses would in this case amount to 5·9 per cent; or, taking into account the increased temperature of the conductors, 6·2 per cent. Thus with one line operating with direct current and the other remaining on the alternating-current system the power transmitted can be increased by 150 per cent. If the second line is also changed over to direct-current working the transmitting capacity of the double-circuit line is quadrupled, whilst the line loss would at the same time be reduced by one-seventh.

The foregoing typical example affords perhaps the best illustration of the way in which the economic problem of applying super-tension direct current to the electrical transmission of energy might be solved. It is to be hoped that manufacturers and users of electrical plant will collaborate with the transmission engineer so as to bring about such a comprehensive experiment.

(7) CONCLUSION.

Having due regard to recent developments in rectification technique, and bearing in mind that further advance in the use of apparatus founded on principles comparatively new to electrical science is inevitable as more experience is gained, it is reasonable to hope that the direct-current system will find an early application to the transmission of electric power at very high voltages. It would appear that, when it does find such an application, direct current will have little difficulty in establishing itself as a power-transmitting medium which is considerably superior to 3-phase alternating current in respect of efficiency, economy, and reliability.

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Discussion before The Institution, 18th January, 1934.

Mr. W. E. Highfield: When any question of high-tension direct current arises one's thoughts instinctively turn towards the only large-scale direct-current system that has been used, namely the Thury series system. It is almost impossible for those who have not seen a series system at work to realize its simplicity and its safety. Contrast a series system with a parallel system, either alternating current or direct current. In a parallel system the insulation is always stressed to its maximum, and if alternating current is employed that stress is subjected to 50 formidable reversals per second. Under short-circuit conditions, the initial rate of growth of current may be of the order of 1 million amperes per second. By the time the protective gear has operated and opened the circuit breakers, the current may be of the order of 5 000 or 10 000 amperes. On the other hand, in the series system the e.m.f. varies with the load, so that the average stress over the 24 hours is very much less than the maximum, and the variations are slow and regular. The current is constant, even under short-circuit conditions. There are no switching surges, because in the ordinary sense there are no switches. Each generator is simply equipped with a slow-moving short-circuiting switch. I do not think another system has ever been devised or ever will be devised which is so safe from these points of view. The series system may employ overhead lines, or, at a very moderate cost, it may be carried underground. A portion of the Moutiers–Lyons system, running into Lyons, is carried on underground cables. These cables are approximately equivalent to those which would be used for 40-kV alternating current, yet they work on 100-kV direct current without difficulty. With regard to parallel systems for direct current, the arc rectifier represents a great advance and it will undoubtedly lead to further research and further knowledge. At the present time, however, it is not possible to purchase a 2 000-kW set to work at 30 or 40 kV, and we have therefore still a long way to go. I should like to mention one point which particularly appeals to me with regard to the rectifier, a point which indicates a complete change in thought. We used to take the utmost care that no apparatus was connected to an a.c. system which had an unsymmetrical wave-form. Consultants, contractors, and the Post Office, all co-operated with this end in view. Nowadays, however, rectifiers which produce exceedingly distorted wave-forms are connected to our systems. I think we shall pay for this change in thought, particularly if it is introduced into a d.c. system connecting together two or more a.c. systems. We should revert to previous practice with regard to wave-forms. That there is a future for direct current for transmission purposes is made clear if we consider what plant we possess and how it developed. On an a.c. system the generator, whether water-driven or steam-driven, is one of the finest pieces of engineering the industry has produced. It is only when 200 miles of transmission line are connected to the generator that troubles are experienced. On the other hand, with a d.c. system there is no difficulty in regard to transmission, whether it be overhead or underground, but the generation difficulty has never been satisfactorily solved. The first power stations were all direct current, and they would only operate commercially with the help of a storage battery which enabled these 1-shift stations to give supply over 24 hours. As power demands increased and the transformer was invented, the a.c. system was developed. Its wonderful flexibility promised to be sufficient to deal with every possibility. Now distances and powers have again increased, and we have to meet difficulties with regard to the transmission line. We have at our command the perfect d.c. transmission line, and the perfect a.c. generator. It is logical to continue our investigations along the lines which have been indicated and surely we shall not lack a genius who will, one day, mould these two things into one harmonious whole.

Mr. J. R. Beard: I am disappointed to find that the paper throws no new light upon the subject with which it deals. The recognition that direct current has certain advantages is as old as the industry, but, as the author points out, renewed interest has been taken in direct current of recent years owing to the development of new means for a.c./d.c. transformation. On this particular point, however, he has little more to say than that "new developments in the technique of arc rectification go to indicate that a practical solution of the problem of high-tension direct-current transmission will be found in the not far-distant future" and that "serious consideration ought to be given to the transvertor, which affords a rational solution to the transmission problem." I do not think that at the present time he is justified in saying that "alternating current cannot compete with direct current where transmission on a similar scale is concerned" or that "direct current can form an economic link between the source of energy supply and the consumer." Turning to the more general aspect of the subject, I think one is justified in challenging the assumption that direct current is the natural form in which electricity should exist. Is not this idea chiefly due to the fact that the study of electricity developed from the primary battery? In modern practice alternating current is the more natural form; even the author takes it for granted that alternating current can be more easily generated than direct current, and that it will be used in distribution. Therefore if direct current is to be employed for transmission, it must only be because of some outstanding economic advantage. The only direct economic comparison in the paper—the Table on page 7—shows that the anticipated saving is only 5 per cent, and even then the estimates for d.c. transmission must be based on figures which are very theoretical. Leaving out of consideration the difficulties, problems, and limitations, of d.c./a.c. conversion plant, which is admittedly at an experimental stage, and dealing only with the transmission line itself, I should be interested to know what data are available to demonstrate that a conductor insulated to withstand a certain a.c. voltage to earth can equally satisfactorily carry direct current at $\sqrt{2}$ times the voltage under commercial conditions. In order to provide data for any future consideration of d.c. transmission, steps ought to be taken to conduct an extended comparative trial on insulator strings carrying direct current and alternating current respectively in various types of climates. Such a trial is important because it seems to be generally agreed that direct current is only attractive on a very large scheme, and there are obvious disadvantages in embarking on new methods in a large scheme unless one is quite sure of the basic assumptions. Direct current is notoriously liable to trouble from moisture, and I doubt whether during the recent fogs it would have been possible to keep a d.c. line at the same voltage as the r.m.s. alternating-current value, let alone at $\sqrt{2}$ times this figure. I can see that from the underground-cable point of view direct current may be preferable. It is well known to distribution engineers that on lower-voltage systems d.c. networks give much more trouble than a.c., but in transmission at high voltages troubles of this kind might be minimized. One of the most important possible fields for d.c. transmission would therefore seem to be where cables are essential, as in crossings of wide stretches of water. For normal routes we require much more justification than the author gives for assuming that a high-voltage d.c. cable is no more costly than an overhead line. Other points upon which he does not touch are the means for switching d.c. lines, the effect of lightning, and the problem of protection. Is it not possible that the stability of the d.c. transmission line may be offset by instability of the converting apparatus under short-circuit conditions? The author makes one assumption which gives a fundamentally wrong impression of the possible advantages of direct current. In paragraph (iv) on page 3 he states that a double-circuit 3-phase a.c. 132-kV line can be utilized as a triple-circuit d.c. line with earthed neutral operating at 370 kV between positive and negative, and that under these conditions for the same power transmission the line loss with direct current will be one-sixth of that occurring with alternating current. This point is elaborated further on page 8, where it is stated that on such a line the transmitting capacity could be quadrupled whilst reducing the line loss by one-seventh. These calculations assume that a circuit which when carrying alternating current is worked at $(132/\sqrt{3})$ kV to earth, can operate at 185 $(= 132\sqrt{2})$ kV to earth on direct current, i.e. that the a.c. line is insulated to earth for the full voltage between phases. The earthing of the mid-wire of the 3-phase d.c. system is an essential part of the scheme, and it is therefore reasonable to assume that the comparison is with an a.c. system in which the neutral is also earthed. In fact, from the voltage and size of conductor mentioned I think the author has in mind the British grid system, which has the neutral solidly earthed at each transforming station. The normal voltage to earth to which the insulation of the a.c. system is subjected is therefore only 76 kV, and I fail to see that he would be justified in applying a d.c. voltage of more than 107 kV. The comparative figures mentioned in the paper are therefore purely fantastic. A further point which arises is whether on the basis of the author's own figures the corona loss would not be so high as to make the transmission unworkable. Even if it be assumed that such high d.c. voltages could be dealt with by the insulation, it is still open to question whether the suggested superiority of direct current exists. If one bases the comparison on the d.c. voltage to earth being $\sqrt{2}$ times the existing a.c. voltage to earth, then the line loss with direct current is reduced to half of that with alternating current, instead of one-sixth. The author gives the line loss of the a.c. system as 7·2 per cent, so that on a reasonable basis of £2 10s. per kW + 0·1d. per unit, and 50 per cent load factor, the value of the loss on 100 miles of double-circuit a.c. transmission would amount to about £25 000 per annum. If this is reduced to half, the saving is £12 500 per annum, which represents £125 000 when capitalized at 10 per cent. In order to obtain this saving, however, 160 000 kW of d.c./a.c. converting apparatus would be required, on which it would therefore only be economic to spend £1·28 per kW, a considerably lower figure than any I have so far seen suggested. The paper need cause no anxiety to the engineers responsible for the grid scheme. In my opinion, if this had been planned 10 years later than it actually was, it would still have been designed on an a.c. basis.

Mr. T. N. Riley: In Section (2) the author states: "As in direct-current transmission no dielectric losses occur, and insulating materials can thus be stressed many times more severely than with alternating current, cables can be used even at very high d.c. voltages." It is not the dielectric loss as such which limits the voltage possible on a.c. cables: in good present-day practice power factors of the order of 0·004 are obtained. If the losses were entirely due to the intrinsic conductivity of the dielectric and were constant, a power factor of three times this value could be accepted without anxiety from the operating point of view. The losses would not lead to undue heating of the dielectric. Such a high figure would not be approved for an impregnated-paper cable, only because it would indicate the presence of moisture or other impurities which might give rise to ionization or other trouble in service. What really sets a limit to the voltage is the onset of internal discharges, of which increased losses are an indication, and it is by the adoption of means to prevent such ionization that most progress has been made in recent years. When direct current is employed we get rid only of the pure losses due to the ohmic resistance of the dielectric; that is, the losses which are relatively unimportant. We do not necessarily eliminate the discharges in voids which create ionization loss. If the voltage is sufficiently high these will still damage the dielectric and give rise to trouble in service. We cannot increase the direct-current voltage many times, but only until a corresponding breakdown voltage for the internal voids has been reached; that is, probably about the peak value of the a.c. voltage. I do not forget that—as Mr. Highfield has reminded us—cables said to be suitable for 40 kV alternating current have been installed for 125 kV direct current and have operated successfully, or that tests on samples of impregnated paper have given d.c. breakdown values from $1\frac{1}{2}$ to $2\frac{1}{2}$ times the peak value of the a.c. breakdown voltage. Estimates of this kind, however, always ignore two factors; first they are based on short-time tests with no heating cycles, and in the second place a given thickness of dielectric is now used on much higher a.c. voltages than were formerly considered safe. All d.c. service tests have been not only on constant load on the Thury system with no temperature fluctuations, but on less than rated voltage, since this is not reached until the line is employed for its maximum power capacity. If, as is suggested, we operate on a constant-voltage d.c. system, there is no reason why we should expect to be free from the same thermal instability troubles as have arisen with a.c. cables. Omitting estimates based only on short-period tests, the highest-voltage a.c. cable tested under service conditions is the one described by Emanueli* at the High-Tension Conference last year in Paris. This works at 220 kV 3-phase, or 127 kV to earth, and has a working stress on the dielectric of about 11 000 volts per mm. Assuming we could accept the peak value of the stress (say, 15·5 kV per mm) as the maximum possible d.c. stress, and considering a cable which is as large as one can reasonably handle, i.e. 1 in. core and 3 in. diameter over the lead, we find that about 200 kV to earth is the limit deducible from present-day a.c. cables, instead of the author's value of 300 kV, or the very high estimate of 500 kV to earth which has been given by Henriksen.† The latter figure, I believe, was obtained from Delon, who had a good deal to do with the cable of the Moutiers–Lyons scheme. His proposal would involve a stress of 37 kV per mm in the insulation, which is altogether too close to breakdown for safety in service. Considering the problem from another angle, we may start with a maximum d.c. breakdown stress of 50 to 60 kV per mm. Taking the higher figure and allowing a factor of safety of 2 between breakdown and test voltage, and a further factor of safety of 2 between test and operating voltage, we again obtain 15 kV per mm as the safe stress. We might be able to reduce this margin, but the same technique would also enable us to raise the a.c. transmission voltage of the cable. One other factor should be taken into account. There is some evidence that under a d.c. stress the fall of potential in a liquid or impregnated-paper dielectric is not distributed as it would be if the dielectric were of uniform resistivity throughout. There is probably a tendency to form high-resistance films at the terminals, and, if the potential drop is concentrated there, sufficiently high stresses may occur to produce breakdown, while the bulk of the dielectric has not been subjected to dangerous stress. This phenomenon, which does not occur under a.c. conditions, might further limit the possible d.c. voltage. I therefore feel that if a solution is found which enables us to operate cables at d.c. voltages exceeding 200 kV to earth, it will probably not depend upon the kind of insulation in use at present.

Dr. W. G. Thompson: The author demonstrates that d.c. transmission is suitable when the power to be transmitted is large and the distance great. It follows from this, as the converse and also from voltage-transformation considerations, that connected to a d.c. transmission system we must have subsidiary a.c. networks.

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* Report of the E.H.T. Conference, Paris, 1933, Paper No. 49.

† *Ibid.*, Paper No. 25.

It would be interesting if the author would state the position of the invertor in regard to this question. The best solution to the problem of overcoming the difficulties in connection with the invertor for dealing with wattless load is that put forward by Dr. Petersen, whereby the amount of wattless load to be transmitted can be compensated by a machine whose output is equal to about 19 per cent of the total wattless kVA. I should be glad if the author would confirm this. On page 3 it is stated that the skin effect is characteristic of alternating current at high voltages. I prefer to regard the skin effect as purely a current phenomenon, depending on the current density and the frequency. In Section (2) the author states that the critical voltage for corona is 41 per cent higher in the d.c. case than in the a.c. case. I once carried out some investigations on a length of overhead conductor of about 6·9 metres, with a view to estimating the relative corona loss with direct current and with alternating current.* The loss was measured by means of a co-axial cylinder arrangement of conductor, outer guard-rings, and condenser. The measuring cylinder was 2 metres in diameter. The a.c. losses were measured by means of a Schering bridge, and the d.c. losses by a suitable galvanometer. Despite certain inherent limitations of this method, it was possible to gain from it some idea as to the relative losses (see Figs. A and B). The data obtained suggest that (i) in single-wire d.c. transmission it is advisable to make the overhead conductor positive, and (ii) in 2-wire d.c. transmission the negative conductor should be higher than the positive, or alternatively the area of cross-section of the positive conductor should be reduced. Tests were also performed under rain conditions. Owing to the limited space available for the apparatus, the insulators used to support the conductors were somewhat highly stressed, and under rain conditions certain insulator failures took place. These failures occurred more frequently under d.c. than under a.c. voltage conditions. The trouble arose from the direct-current arcs which were present at the metal fittings of the insulators. A d.c. arc is continuous, and it is therefore possible that intense local heating took place where the arc left the metal cap and came on to the moisture film on the insulator surface. The remedy for this is to modify the insulator design. With regard to cables, an important point to bear in mind is the question of electrical endosmose. Prof. Thornton has suggested that this effect is due to the negative ions moving towards the positive core of the cable and causing motion of the moisture particles in that direction. The advantage of d.c. transmission for under-sea work is very great, as it obviates the necessity for laying, say, three single-core a.c. cables. Provided the difficulties in connection with electrical endosmose, accompanied by an additional hydrostatic pressure on the outside, can be satisfactorily overcome, a d.c. cable for this sort of transmission should prove exceedingly useful. Turning to the question of network stability, this is not merely the stability of the transmission line; the whole of the connected apparatus must be considered, and at present we have very little knowledge of how an invertor behaves on fluctuating power factors and similar system variations. I should like to mention that the atmospheric-arc valve designed by Prof. Marx really involves no new principles whatever; it represents the intelligent combination of many principles which have been recognized for some years and about which almost everything is known. The arc is established under perfectly-controlled conditions and is extinguished as a result of the arrangement of the air flow. There is nothing such as de-ionization and other similar effects which are sometimes met with in vapour, and are not yet clearly understood, to be contended with in the Marx rectifier. The problem of international high-tension d.c. transmission over great distances, touched

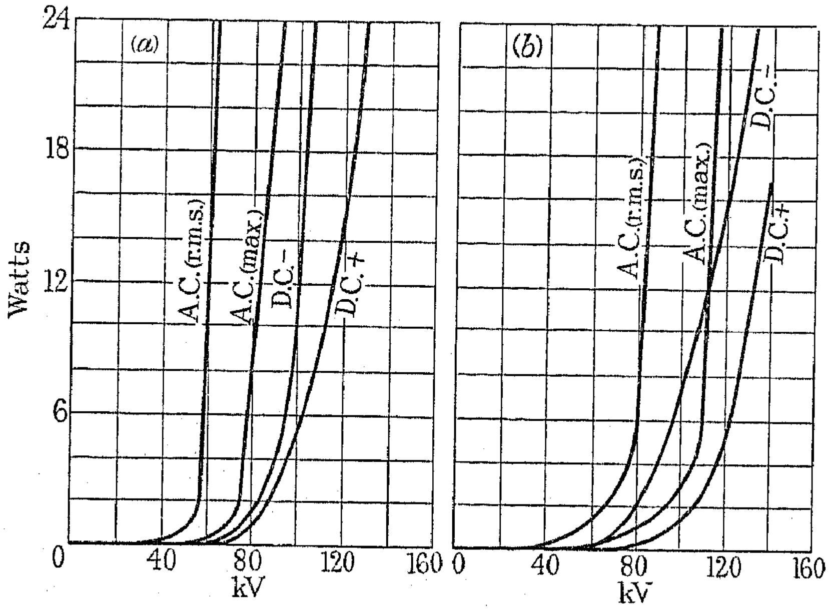

FIG. A.—Comparative losses with a.c. and d.c. corona. (*a*) 7/3·0-mm stranded copper. (*b*) 19/2·84-mm stranded copper.

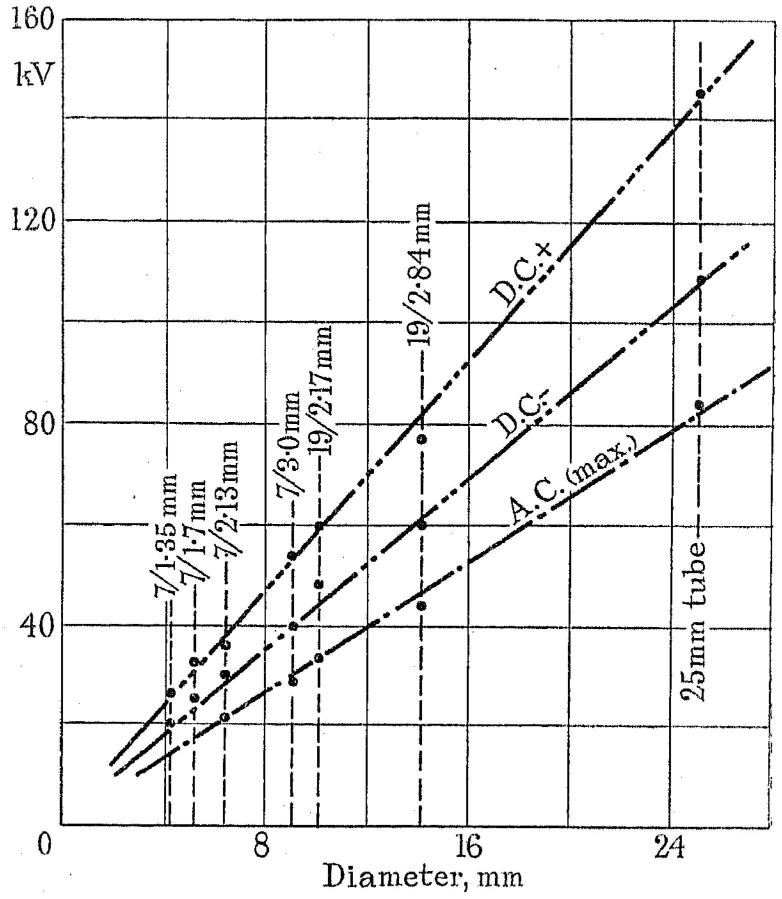

FIG. B.—Relation between corona starting-voltage and conductor diameter.

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* See also E. MARX and H. GÖSCHEL: *Elektrotechnische Zeitschrift*, 1933, vol. 46, p. 1112.

on in Figs. 1 and 2, is at present somewhat outside the control of the electrical engineer. Whether certain European countries, in these days of adverse trade balances, are prepared to accept additional imports in the form of thousands of kWh is a matter for political economists to decide. On the other hand, it is refreshing to see Europe take on the aspect of an economic unit, even if it is only through diagrams relating to high-tension d.c. transmission schemes!

Mr. W. M. Mordey: The author wonders whether any of this audience was here 27 years ago when Lord Kelvin spoke on the subject of the present paper. I was in the chair, and I fancy that a good many more of those here to-night were present then. It was the occasion of the Institution's first paper on high-tension direct current, read by Mr. J. S. Highfield.* Lord Kelvin opened the discussion by saying " I have never swerved from the opinion that the right system for long-distance transmission of power by electricity is the direct-current system." He gave some reasons for that opinion and quoted what Lord Rayleigh had said in a private conversation years before, that he rejoiced to see alternating current coming in " because the whole world will now learn the subtleties of electrical science, . . . and after that they will come back to the continuous current." My attention has been drawn by Mr. W. Wilson to the fact that the author omits all British names from the list that he gives of the early workers in this field. Mr. Wilson suggests that my name should appear in the list, and asks whether it is not a fact that in 1886 I designed some small high-tension d.c. power plants of which he gives particulars. I had forgotten it; but it is a fact that my former employers, the Anglo-American Brush Co., made at that time some such plant which I had designed. Mr. Wilson refers to such a plant that was sent out to a gold mine in New Zealand. The generators were two Brush arc lighters which ran in parallel, giving 2 000 volts and 10 amperes each. A similar plant was installed at a gold mine on the Simplon Pass in Switzerland, and I think there were others. We did not regard these installations as a new idea, as for years we had been making ordinary d.c. high-tension Brush arc lighters and there was no novelty about using them to drive a motor, instead of a string of arc lamps. Any credit in connection with that work should be given to the memory of Charles Francis Brush, of Cleveland, Ohio, who evolved the system in all its essentials about 1877.

Prof. J. T. MacGregor-Morris: One of the drawbacks to the Thury system in its original form is that the current is constant. This being so, the line losses are constant and the system is thus handicapped with these losses throughout the whole of the 24 hours. Some time ago, on the Moutiers–Lyons system the normal current was 80 amperes, but at periods of light load it was cut down, I believe, to 10 amperes so as to reduce the line losses to $\frac{1}{64}$ of their usual value. Can the author give more particulars about what has been done since? According to the paper the normal current is now 150 amperes. In Section (3), does not the author dismiss the d.c. machine rather abruptly, on the assumption that the mean voltage between adjacent commutator segments cannot be more than 25 volts? Is it not worth while to consider the possibility of running the d.c. generator in a compressed gas? If it were worked in a casing at a pressure of 10 atmospheres, the author's figure of 10 000 volts for the commutator voltage could be raised to a much higher value. A possible competitor to the d.c. generator is the copper-oxide rectifier. Although at present its efficiency would not compare favourably with those of other methods of conversion, it has made marvellous strides in the direction of current-carrying capacity. At the recent Exhibition of the Physical Society it was stated that a rectifier of this type had been made which would work at 100 000 volts.

Major A. M. Taylor: Alternating-current engineers seem to have failed to realize that they have in their hands the remedy not only for corona, but also for instability. The advent of the automatically-controlled tap-regulated transformer at once puts in our hands an apparatus which enables us with great cheapness to control potentials at every point of the line, and which consequently gives great flexibility in avoiding corona. By making the booster voltage controllable by the current passing (and not by e.m.f.) we have the means of cheaply and economically boosting into the line, to make the potential vary in any desired way. If we want to make the voltage at the receiving end higher than that of the sending end, in order to avoid corona where the sending end is at a high altitude, it can be done. If we want to avoid corona in passing over a mountain range, we can dip down the potential. This cannot be done with direct current, except at enormous expense both in capital outlay and in working. Altogether, by means of alternating current we can probably get a 30–35 per cent advantage to help us with corona. It is possible to do without synchronous condensers and to close up the power-factor angle (ϕ) all along the line. Instability, so far as the line is concerned, is also simultaneously remedied. This, of course, is of the greatest importance. The question that will at once occur is: What will be the effect of the overloading of the line conductors due to the passage of all the currents necessary for the supply of the booster primaries? I have worked out the case of a double-circuit line 1 200 miles long (Norway to Germany is only 800–900 miles) passing 100 000 kVA at 370 kV, and find that the average overloading required for overcoming reactance drop is only some 2 per cent. This figure is surprisingly low, and still lower figures can be obtained. No doubt the cost of the six phase-compensating stations in the Norwegian a.c. scheme was partly responsible for the great capital outlay and the high working expenditure; and even then there was no guarantee of stability.

Mr. Albert Page: In dealing with transmission problems certain fundamental conceptions are often overlooked. In the first place, there is theoretically no limit to the amount of power we can cram into a minute space. This is borne out by the author's suggestions of stepping up transmission voltages to still higher values, a point of view with which I entirely agree. As regards our own system of transmission, I predict that in 50 years' time engineers will ridicule our present adherence to alternating current. The comparison of the d.c. and a.c. systems outlined on pages 2 and 3 shows that practically all the disadvantages lie with the latter. While the d.c. system has many serious obstacles, such as that of metering at 500 kV, these can be overcome; whereas the corresponding drawbacks to alternating current can never be eliminated no matter what we do. The one outstanding advantage of the a.c. system is that its voltage can be efficiently stepped up and down by means of static apparatus. The mere absence of these means when direct current is employed should, however, intensify our efforts to devise suitable apparatus instead of encouraging us to assume the *laissez faire* attitude of adopting the existing means, which involve so many points of inefficiency. I believe that the day is not far distant when transmission of electrical power from one point to another will be undertaken without any loss whatsoever. It is only our crude methods of utilizing electricity and our inadequate knowledge of the subject which at present lead us to incur a loss. Transmission losses will, I think, be eliminated as the result of a close study of the subject of radiation of heat, light, and electricity. The opinions on this subject which I have held and expressed for many years have recently received confirmation by a report that von Platen has developed a system of the type at which I have hinted, and is to present a paper on his methods to the Swedish Technological Association. I believe the system is being developed at the cable works at Sundzberg, where it is considered that a 500-kV cable could be constructed for precisely the project shown in Fig. 2. Has the author any further particulars of the suggested system, and is he in agreement with my general views on the subject?

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* *Journal I.E.E.*, 1907, vol. 38, p. 471.

Mr. W. E. M. Ayres (*communicated*): I do not quite agree with the remark on page 2 that the power transmission system of which the Moutiers–Lyons transmission by high-tension direct current is such a remarkable example has been accorded little attention in the past. This Thury system has been well described in every civilized engineering country throughout the world, and for a system of less than 20 MW this is a good proportion of publicity as compared with other methods of transmission. All a.c. engineers are fully prepared to admit the limitations of their medium for power transmission over long distances, and that the limitations increase with the frequency. It is not sound, however, to argue from this that the elimination of frequency by using direct current at high tension is a completely satisfactory cure. To what extent are large blocks of power required to be transmitted over considerable distances? Industry, which, with its attendant population, is by far the largest user of power, always tends to gravitate to the power source or at least to districts where power is cheap. In this country the distance from Looe to Lossiemouth is some 600 miles, but there is seldom a gap of more than 50 miles between selected generating stations. Similarly on the 500 miles of the Rheinisch–Westfaelisches transmission line there are 11 generating stations. It has repeatedly been shown that it is cheaper to transport fuel than to transport the resulting amount of power by electrical means; the use of large grid systems lies in the continuity of load, with the advantages gained from diversity. This being so, the only value of the long-distance transmission of huge blocks of power is in connection with hydro-electric schemes where the power can only be transported electrically. Incidentally, the only typical cases cited in Section (5) are hydro-electric schemes of such a nature. The author envisages a high-tension d.c. grid system; is such a scheme at all workable? D.C. systems in parallel are notoriously sensitive to voltage changes, and even a simple series of substations has to be handled with the utmost skill. On an a.c. transmission system the prime movers share load according to the setting of their governors, and voltage-changes due to transmission only affect the wattless distribution. Where d.c. transmission is employed, on the other hand, a difference of voltage may completely unload a station or cause it to "motor." It is the "flexible" coupling of alternating current which has made it possible to operate large grid systems. The "rigid" coupling of direct current might easily lead to large-scale disasters. From this point of view also, the one case where the transmission of large blocks of power is justified occurs in hydro-electric areas where by single connection into another system this power can be utilized. The author states on page 8 that "the difficulties have resided in the efficient conversion of current on a large scale and at high voltage." Making an assumption which by no means represents the present state of the art, namely that the 1 250 MW of 400-kV direct current can be reliably and efficiently produced and satisfactorily inverted to alternating current at the distributing centres, is the Norway–Germany transmission problem then solved? It is desired to tap loads off at Göteborg and Copenhagen. This inevitably means switching on the h.t. side. Where is even the suggestion of development of a 400-kV direct-current switch? Questions of arc rupturing and rupturing capacity are much more difficult with direct current than with alternating current, which passes through zero twice every cycle. Suppose, however, that the tee-off loads are neglected and that switching can be done on the grid of the rectifiers, thus quenching the voltage in a quarter of a cycle; what will the enormous amount of stored magnetic energy do in discharging itself? If loads are tapped off there will be high-tension metering, and for double-circuit lines there will be protective devices; neither of these exist, and they present acute problems. Finally, it must be remembered that d.c. systems are as susceptible to transient phenomena as are a.c. systems, and that every switching operation develops a steep-fronted wave. If this is fully taken into account in the design of the transmission line, will even the small capital advantage shown in the Table on page 7 be realized? The paper admittedly puts forward some aspects of the problem, but when the possible scope becomes so limited and the unsolved difficulties so great the aspects chosen by the author tend to create a false perspective.

Prof. J. K. Catterson-Smith (*communicated*): I am particularly interested in the information given by the author in regard to the development of the Marx atmospheric-arc valve. I notice that an axial magnetic field is provided, unless the magnetic poles are consequent, and, recalling that a transverse field was used in the Poulsen arc (a form of high-frequency invertor), I should like to know whether the author can give the reason for this. Successful operation of the Poulsen arc depended upon extremely rapid de-ionization of the arc space, which was brought about by the use of a hydrogen or hydro-carbon atmosphere together with the magnetic field, and in addition the cathode was carbon and the anode a water-cooled copper electrode. I recall the inherent low efficiency of the Poulsen arc, even in the large sizes, and, hope that at 50 cycles per sec. the losses in an invertor are much reduced as compared with those at, say, 10 000 cycles per sec. The origin of the almost universal adoption of the a.c. system was the limitation to the design of generators imposed by the ordinary mechanical commutator, and it is natural to anticipate that as soon as it is established that mercury arcs or other thermionic devices can be used as commutators we may look for revolutionary changes in both plant and transmission. It appears to be recognized that invertors require the addition of devices, analagous to interpoles, for securing "forced commutation" in order that they may be operated at a high value of power factor on full load. Recently-published results indicate that there are several ways in which this may be accomplished and invertors worked with the angle of ignition retarded by 180°. Under these conditions the maximum transference of power from the d.c. to the a.c. systems takes place with values of power factor and efficiency which are satisfactory. I have been impressed by certain difficulties, in working invertors, such as the possibility of short-circuiting the d.c. system, should failure of the a.c. supply occur, and the consequent necessity for high-speed grid-bias protective devices. Prof. MacGregor-Morris has drawn attention to the limitation of the mean voltage between adjacent commutator segments of a machine, the value of which is assumed by the author to be 25 volts, and has suggested that some experimental work on this aspect of commutation is worth consideration. In 1910 I carried out some such experiments on a small scale at the University of Liverpool, along the lines of investigating the possibility of using compressed air as the medium in which the commutator and brushes are operated. An experimental d.c. interpole generator was constructed with a frame suitable for an internal air-pressure of 200 lb. per sq. in. The commutator was designed for 140 volts per segment, and the machine gave a full-load output of a few kilowatts at about 5 000 to 6 000 volts. There was no tendency to flash-over even on short-circuits, and both visual and oscillographic observations of the commutation conditions indicated that in this way very high values of the voltage per segment might be employed with safety. At that date there appeared to be little or no demand for a high-voltage commutator, and the investigation had to be abandoned. Some similar experiments on a commutator and brush gear immersed in oil proved unsuccessful. I am therefore of the opinion that the limitation assumed by the author should be taken as applying to normal commutators, and that a value of about 4 to 6 times his figure could be obtained if required. Thus some of his arguments on page 4 require qualification. He does not emphasize sufficiently the important advantages, possessed by valve apparatus, arising out of the possibility of utilizing grid control for interrupting the current and thereby making it possible to dispense with mechanical switchgear. It might be gathered from the paper that the high current capacity of a circuit carrying direct current, when compared with that used for 3-phase currents, is a feature possessed only by high-voltage systems. This is not the case, as low-tension cables of given weight and insulation may be rated at about 100 per cent greater load capacity with direct current than with alternating current. A further point is that, just as the d.c. motor is widely used for traction, so it is once again finding favour for factory drives, a number of which are now being changed over to d.c. motors. In the past, attention has been drawn to difficulties experienced on account of the difficulty of insulating the negative side of the system from earth; has the author any comments to offer on this point? On page 3 it is stated that "alternating current tends to gravitate away from the centre of the cross-section." I suggest that it would be more appropriate if the phrase "gravitate away from" were replaced by the word "leave." Also the term "super-tension," in the last paragraph of Section (6), page 8, is undesirable.

Colonel R. E. Crompton (*communicated*): I have obtained from Mr. Vidar Ekström the following particulars of what has been called the Glesum system of d.c. transmission, and which seems very likely to be a commercial success. The system is based on certain fundamental principles worked out by von Platen, one of the inventors of the Electrolux refrigerator. For the production and conversion to mechanical energy of high-tension d.c. energy it is necessary to employ revolving machinery; the convertors for the direct transformation of high-tension direct current to alternating current must also revolve. This means that alternating voltages and currents are produced in the revolving machine, and these by suitable commutators are rectified to direct current in the outer circuit. Briefly, the fundamental principles given by von Platen are the following. (1) It is essential to concentrate on obtaining a simple commutator, which will be foolproof against the highest voltages, even if the commutator problem be complicated in certain other respects. It is possible in this way to reduce the size of the commutator, so as to be able to enclose it, at very high voltages, in a high-pressure container. Compressing the gas in the container in which the commutator revolves will give the gas the necessary electric strength. (For a commutator designed for transmissions of 30 000 kW, 100 000 volts, the container would be of less than 30 cub. ft. capacity.) (2) In order to get a simple commutator it is necessary to generate the voltage in a small number of windings instead of in a large number, as is the general practice. The commutating voltages to be handled are in this way very considerably increased. (3) The difficulties of getting sparkless commutation, which arise owing to the heavily-increased commutating voltages, will be compensated to a certain degree by the simplified commutation owing to the fact that the number of generator windings can be reduced. Experiments have proved that these fundamental principles are correct. A high-tension commutator with 20 mm between the commutator segments has been successfully worked up to 13 000 volts between adjacent commutator segments. With increased air pressure it has proved possible to increase the voltage between the segments to 75 000 volts, but the commutation limit is certain to be still higher. The Glesum system consists of a generator for producing high-tension d.c. energy, a motor for converting the d.c. energy into mechanical energy, and finally a transvertor for direct transformation of direct current from one voltage to another or of high-tension direct current to ordinary 3-phase alternating current. The Glesum generator and the Glesum motor can therefore be characterized as something between an ordinary d.c. machine and a synchronous machine. Hence the voltage-producing windings are generally placed in the stator, whereas the magnetizing windings are on the rotor. The voltage curve used is not sinusoidal but generally trapezoidal, there being intervals at which the voltage is zero. For high-tension d.c. work the windings producing the voltage, in the Glesum machine, are designed for a comparatively low voltage, which is then stepped up by static transformers. The voltage from these transformers is then rectified in the high-tension commutator. By means of the Glesum transvertor it is possible to pass directly from high-tension direct current to ordinary 3-phase alternating current, or from high-tension to low-tension direct current, or vice versa. The above-mentioned results have already been achieved on a d.c. transvertor rated at 440 000–110 000 volts at an output of 220 kW, with the high-tension commutator enclosed in a compressed-air container. Experiments are at present being carried out on a generator for 30 kW, 12 000 volts (max.), with a high-tension commutator working in normal air pressure. It is no exaggeration to say that the results of the experiments made up to date fully come up to expectation.

Mr. E. O. Taylor (*communicated*): One advantage of d.c. transmission which is not mentioned in the paper is the fact that a rectifier will operate equally well over a wide range of frequencies, so that the generators and prime movers supplying such equipment can be designed to operate at the speed which gives the most economical design instead of being governed by the necessity of generating at 50 cycles per sec. Further, in a variable-head hydro-electric station, such as is suggested for the San José tidal power scheme, this fact could be made use of to enable a.c. generators operating at a variable speed to be employed. Although the author shows that a given 3-phase line can carry considerably more energy if direct current is employed instead of alternating current, he gives no data regarding the relative costs of a.c. and d.c. lines. I have recently investigated this matter and have worked out the cost per mile of the most economical design of double-circuit line at various loads for both a.c. and d.c. transmission. (By "most economical design" is meant the design giving the minimum annual cost, i.e. annual charges plus cost of losses.) The results of this investigation are shown in Figs. C and D, and the detailed figures for a line transmitting a load of 50 000 kW are given in Table A. It is assumed that the load is transmitted continuously. A saving of about 25 per cent results from the use of direct current: the actual figures depend, of course, on the values assumed for costs of materials and energy lost, but the saving

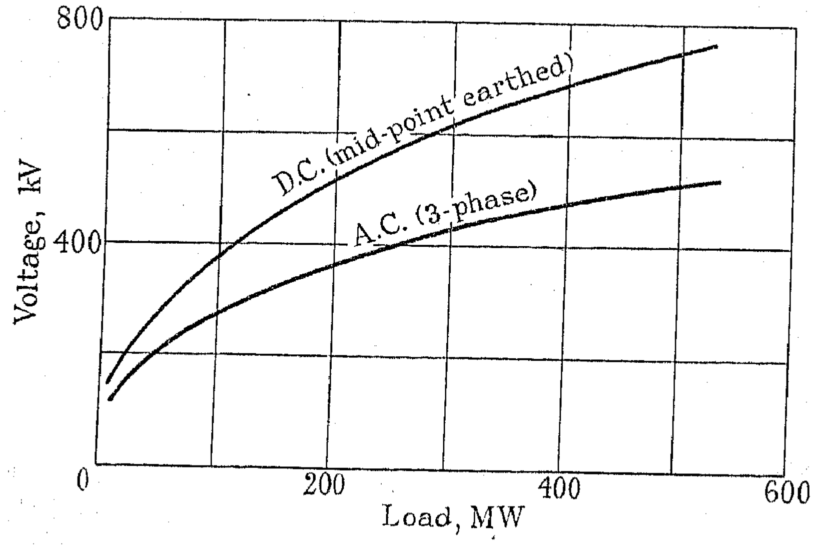

FIG. C.—Line voltage of most economical design of transmission line for various loads.

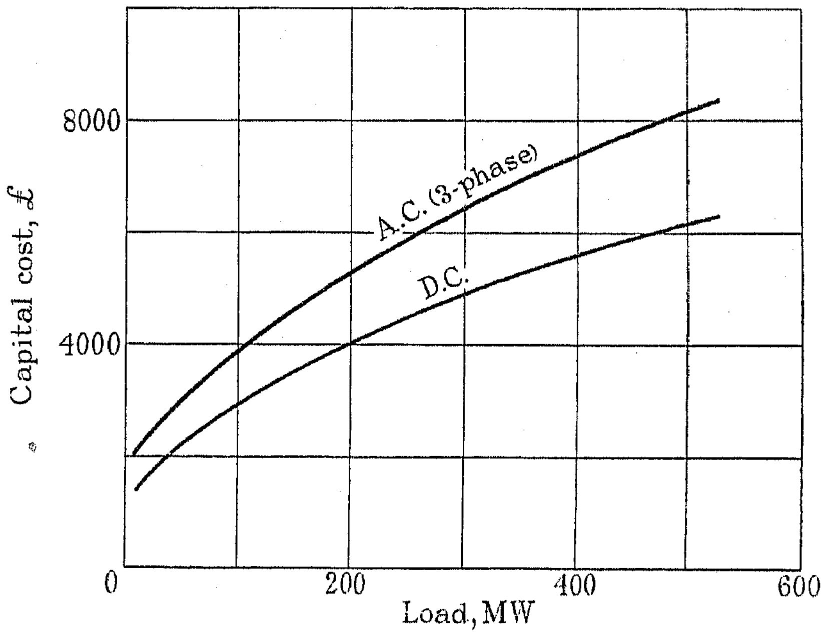

FIG. D.—Capital cost per mile of most economical design of transmission line for various loads.

TABLE A.

Data Regarding Most Economical Design of Transmission Line to Transmit 50 000 *kW Continuously.*

	A.C.	D.C.
Kilovolts to earth . .	119	140
Line kilovolts . .	206	280
Span, ft. . .	1 280	1 000
Capital cost per mile, £		
Conductors . .	730	620
Towers . .	1 540	970
Insulators . .	730	610
Total . .	3 000	2 200
Annual cost of losses per mile, £	88	82
Total annual cost per mile, £ . .	448	339
Percentage saving by using direct current		
Capital cost . .		26·7
Annual cost . .		24·3

will be similar for any normal values of these. If the cost of a d.c. substation is greater than that of an a.c. substation, the above savings will to some extent be neutralized and for each particular load there will be a certain length of line below which a.c. transmission would be cheaper. The rating and cost of switchgear in an a.c. station depend not on the normal load of the station but on the short-circuit kVA of the system to which it is connected. I suggest that, in the d.c. case, switching should be carried out by control of the grids in the rectifiers or invertors themselves. Would this method of switching be suitable for dealing with short-circuit currents, and if so would it influence the size and cost of the rectifier unit? I should be glad if the author would indicate the relative costs of an a.c. and a d.c. substation for the same service. Finally, as there appears to be the possibility of economic success for schemes considerably smaller than those described in the paper, and as the latter in any case appear to have little prospect of success on general economic and political grounds, I suggest that it would be of value if investigators gave their attention to schemes having a more reasonable chance of being carried through.

Mr. H. P. Young (*communicated*): On page 3, in discussing the suitability of d.c. cables for very high voltages, the author omits to mention the increased difficulty of maintaining the insulation of the negative conductor, owing to osmotic action. This is surely a point of major importance, especially in the case of submarine power cables operating at such very high potentials as 300 kV. The author probably has in mind cables of the pressure type: perhaps he would give some indication of the precautions necessary to combat this additional risk of breakdown, especially at the terminals of the lines. The inability of a d.c. transmission system to carry reactive kVA would appear to be a serious disadvantage in the case of a line interconnecting power stations, and the trend of future developments, referred to in column 1 on page 6, indicates that most lines will operate in this manner. The station receiving power will have to supply only part of the power demanded by its network and the whole of the reactive magnetizing kVA. The generators will thus operate at a low power factor, which will adversely affect the operating conditions of this station unless special apparatus is installed to supply the deficiency in received magnetizing kVA. If synchronous condensers are employed for this purpose, the short-circuit kVA of the system may be largely increased. The Table on page 7 shows that a saving of only 5 per cent can be achieved by the adoption of d.c. transmission with mercury-arc rectifiers and invertors, as compared with alternating-current transmission. In a scheme of the magnitude referred to, such a small saving would not appear to be a sufficient inducement for the adoption of the d.c. scheme, especially with 23 miles of submarine cables. Although a great saving can undoubtedly be achieved in the cost of the line, as indicated in the impressive example on page 8, the necessity for, and cost of, the additional converting and inverting apparatus, all of which is liable to breakdown, will operate generally against the adoption of the d.c. system. At the present time, at any rate, there appears to be little evidence to justify the author's final paragraph.

[The author's reply to this discussion will be found on page 31.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 9TH JANUARY, 1934.

Mr. B. L. Goodlet: I have attended several international conferences where d.c. transmission has been on the agenda: the consensus of opinion would appear to be that this system presents considerable advantages for long-distance work but that available methods of generation and inversion are unsatisfactory, and that something new is needed. In the last few years such new work has been carried out in Germany by Prof. Erwin Marx, of Braunschweig. In my opinion the Marx rectifiers and invertors are very promising. I should like to say a few words about a paper by Skilling* which revives the old idea of the half-wave transmission line. Such a line is compensated for charging kVA, and the voltage is the same at the sending and receiving ends except for line loss. Stability is also good, provided that the length of the line is rather over than under the half wavelength. The length of the half-wave line at 50 cycles per sec. is, however, 3 000 km. This length can be reduced by increasing the transmission frequency, this being the solution suggested by Skilling. There is, however, another method, namely to load the line in the same way as a telephone cable. This solution has been considered in Russia. The main difficulty of the half-wave line is that the voltage at the mid-point of the line is higher than at the ends and varies with the load. If the receiving end is short-circuited the mid-point voltage tends to infinity, except for losses. To guard against this it has been suggested that a safety gap should be placed at the mid-point; when this breaks down, the line becomes a short-circuited quarter-wave line, the current at the sending end of which must be zero. There is therefore no difficulty with the sending-end circuit breakers.

Dr. J. L. Miller: Undoubtedly there is a case for d.c. transmission at very high voltages if transmission of large blocks of power over very long distances is required. Many of the problems associated with such transmission systems have been discussed at recent meetings of the World Power Conference and of the International High-Tension Conference. The main criticism of the scheme arises from the question whether it is really desirable or necessary to transmit large blocks of power from country to country. It must be admitted that the idea of supplying areas having no coal or water power from other areas having large quantities of water power available, even though these areas may be several hundreds of miles away, does not at all seem unreasonable. The generation of energy hydro-electrically and its transmission over long distances is not, however, the only problem which needs consideration. When an area is several hundreds of miles away from coal-fields the question arises whether it is cheaper and more reliable to transport the coal to the area and generate energy there, or generate at the coal-field and transmit by direct current at 500 000 volts. No doubt the answer depends on whether the coal transport is a straightforward business; where it would be necessary to transfer the coal from rail to ships and perhaps back again to rail, electrical transmission might be cheaper. It would be interesting to know whether any such alternatives have been considered in the past. In the case of areas a few hundred miles from oil-fields, it would also be interesting to know whether it is a financially feasible proposition (compared with d.c. transmission) to transport the oil along pipes and generate energy at the terminus. In the distant future, when perhaps in many coal-producing areas coal mining will cease to be an economic proposition, it may become necessary to utilize tidal power, in which case there will be a need for d.c. generators and hence for d.c. transmission. It is evident that there is no question of replacing existing 132-kV or 220-kV 3-phase transmissions over 50 to 150 miles by d.c. transmissions; the latter are only suggested for very great distances, with conversion to lower-voltage a.c. distribution at the termini. I think this point ought to be more strongly brought out in the paper. There are many problems on which considerable research will be necessary if in the future we are to have d.c. transmission lines. For instance, chemical and static effects, dirt collection on the insulators, and d.c. arcing, may give rise to trouble; and, while the successful working of the Thury system may be cited against these objections, this system operates at only a little above 100 kV, as against the suggested 500 kV. Switching would presumably be carried out in the conversion equipment itself, but we do not know what difficulties would be encountered with large equipments; further, large conversion equipments have still to be produced. Considerable research would also no doubt be required before simple and accurate measuring arrangements were obtained. Finally, we do not know how the conversion equipments would react to direct lightning strokes or to travelling voltage waves of 2 or 3 million volts, nor can we prophesy what would happen under short-circuit conditions.

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* *Transactions of the American I.E.E.*, 1932, vol. 51, p. 51.

Mr. L. Romero: I cannot see how the author reaches the conclusion that a 132-kV a.c. 3-phase line could be used for 370-kV direct current. The peak voltage to earth on the 3-phase 132-kV system is only 107 kV, and he is proposing to increase this to 185 kV, which is the peak voltage between phases on the a.c. system. It would appear from this that he has confused the voltage between phases with the voltage to earth. If this correction is made, the d.c. voltage which could be used is reduced from 370 kV to 214 kV, and the economic advantages claimed for direct current will have to be reduced proportionately.

Mr. G. H. Sammons: In presenting his paper the author did not make it sufficiently clear that the high-voltage d.c. system is not suitable for a grid but is intended solely for a simple single-line interconnection between two points. Such a system would have no switches in the d.c. circuit (a big advantage), but would be controlled by means of a small low-tension grid switch or exciter switch on the rectifier. By far the biggest problem to be solved (and no doubt it will be solved, before this system attains consistent reliability) is the problem of the insulation of the line. One has only to recall experiences on low-tension d.c. networks to realize how difficult this will be.

Mr. J. W. Thomas: What would happen in the event of a short-circuit occurring on a d.c. system working at a very high voltage, seeing there would be no reactance in the circuit to prevent the building-up of very large currents? The author states, on page 4, "Finally there is the problem arising from the inability of a direct-current transmission line to carry reactive power." Perhaps he would explain this more fully and indicate whether it has something to do with the difficulty of limiting the current that may arise on short-circuit. Turning to Fig. 1, I am very interested in the proposal that Spain should be linked up with Austria across Europe. If we could get the European countries linked up electrically, it might mean the dawn of more peaceful relations amongst the Continental nations.

Mr. S. Farrer: In giving the figure of 370 kV as a suitable voltage between positive and negative wires of a transmission line suitable for operating at 132 kV between lines with a 3-phase a.c. system, the author assumes that the permissible working voltage to earth with d.c. transmission may be considerably greater than 1·41 times the r.m.s. value of the voltage for a.c. transmission. Whilst this may be true for a cable system, there seem to be several reasons why the reverse would be true for outdoor insulators. The rate of dirt accumulation on insulators would be more rapid, and the deposit more extensive, with direct current. Also the voltage distribution on insulators, particularly on suspension strings, would be very indefinite and would depend largely on the insulation resistance of the separate units or sheds at any moment: owing to dirt deposits, brush discharges, or rain, this would be very erratic and give rise to a variable distribution of stress in the insulators, resulting in indefinite performance—especially under bad conditions of weather. In a.c. transmission the charging currents in outdoor insulators are useful in that they determine largely the voltage distribution and the stressing on the individual parts of an insulator, bringing these factors within the control of the designer. It does not appear to follow, therefore, that outdoor insulators suitable for a.c. systems would be suitable for d.c. systems. I should be glad if the author would give some data comparing the wet and dry flash-over values with alternating and direct voltages respectively of such outdoor insulators as would be used on systems above 100 kV. Are any special features adopted in the design of outdoor insulators for operation on d.c. systems to avoid the difficulties mentioned above? It would be interesting to have some suggestions as to methods of line protection and power metering on high-voltage d.c. transmission systems. Mr. Thomas hinted that a European grid could do something to link the nations together; in my opinion, however, the questions of tariffs, voltage regulation, and the right to generate the grid supplies, would provide further causes for argument and discord.

Mr. O. Howarth: The author states in his last sentence that when direct current is applied to the transmission of power at very high voltages it will have little difficulty in establishing itself as considerably superior to 3-phase alternating current in respect of efficiency, economy, and reliability. I think this is rather an optimistic statement, in view of the lack of experience of high-voltage transmission. Generation of the direct current is not the only problem; we have to transmit, distribute, and maintain the supply. Switches will have to be used on d.c. transmission systems if they are to be a success. What will be the effect of the charging current set up when a 1 000-mile d.c. line is switched in? One great advantage of an a.c. system is that its inductance gives it a considerable amount of elasticity, which not only enables it to recover from a disturbance but also limits the currents set up by that disturbance. An a.c. transmission system can be kept alive even after a severe fault; but on a d.c. system there is nothing to stop the rush of current when a short-circuit occurs, and when the switch opens serious trouble may arise. In my opinion the switching problem and the charging problem will be expensive to solve, and the details of protection and metering will be so costly that direct current will not be quite as superior to alternating current as might at first be imagined.

Mr. G. G. L. Preece: I agree with the author that the time will come when d.c. transmission will be tried to a practical extent, and I am sure makers of mercury-arc rectifiers have this possibility in mind. It is indeed only the question of finance which has stopped some very large experiments with d.c. transmission being undertaken in this country. Mr. Woodhouse, of the Yorkshire Power Co., has offered a portion of his line for these experiments. Manufacturers, the Central Electricity Board, and even the Electrical Development Association, might take a hand in the work; it is from some such combination that the money should come for experimental research. So far as I know, the mercury-arc rectifier manufacturers have not met with too great difficulties as regards the higher voltages. Some are certainly prepared to go out for 100 000 volts at fairly large currents, and, although they have not yet tackled units of 50 000 or 60 000 kW, they have manufactured fairly large sizes. There are a number of rectifiers in this country nearly as large as, if not equal in size to, the one shown by the author. Some of these give a current output exceeding 4 000 amperes. In England there are also a few plants fitted with grid control. The Marx rectifier seems to offer some interesting possibilities, and no doubt we shall hear of these later on. Has the author any data as to possible electrolytic effects associated with high d.c. voltages? I should welcome his views on what might happen if we changed over to d.c. transmission.

[The author's reply to this discussion will be found on page 31.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 15TH JANUARY, 1934.

Mr. H. H. Taylour: In view of the large amount of information published in recent years concerning the possibilities of mercury-arc and atmospheric-arc devices, I cannot help feeling a little disappointed that the paper is in the nature of a survey of what are now well-known principles. A reasonably detailed proposal could, on existing data and without undue expense, be formulated incorporating—in addition to lay-out—sufficient suggestions in respect of means for control, protection, and metering, to furnish the basis of a discussion which would not be confined merely to general considerations. The fact that the very real advantages of direct current are present in the transmission line and not in the generating and distributing systems (except in very special cases) suggests that the problem mainly reduces to the provision of d.c. links between a.c. systems. This can be effected by installing converting plant, static for preference, at each end of the lines, like the switchgear of the familiar a.c. lines. The static convertors, in addition to their primary function of a.c./d.c. or d.c./a.c. conversion, would also constitute the switching and controlling means for their own particular lines. The feasibility of using transmission lines possibly thousands of miles in length without subdivision is very debatable, if only from the point of view of discriminative protection. I suggest that a series of d.c. lines of 200 or 300 miles apiece, linking up with each other via the a.c. systems of the larger load centres along the transmission route, is a more practicable proposition. Moreover, with this scheme the reversal of line voltage in dependence upon the direction of power flow when vapour-arc convertors are used does not constitute a serious difficulty, as teeing-off will normally be performed only via an a.c. system. In fact, the periodic reversal of line voltage may to some extent offset the fouling experienced on the negatively-situated insulators of overhead high-voltage d.c. lines. In conclusion, may I ask the author why he considers it unlikely that a 10 000-kW mercury-arc unit could be made to operate reliably at voltages exceeding 20 to 30 kV? Apart from a few attempts to adapt existing low-voltage designs to high-voltage working, it would appear that no serious effort has been made to do so. Indeed, if one can judge from the performance to date of units of this type, there seems to be no reason why 100 kV to 200 kV should not be attainable if the problem is attacked with due consideration to the conditions encountered.

Mr. R. H. Rawll: A certain amount of the discussion has tended in the direction of comparing the a.c. grid system in this country with the ideal d.c. transmission system. I think we ought to view this matter from the correct angle, remembering that in this country the grid is essentially not a transmission system but a busbar system. The author clearly points out that the cases considered in the paper involve long distances of transmission. Many of the factors which decided the system adopted for the grid do not apply to such conditions.

Dr. C. C. Garrard: Electrical engineers have not been mistaken during the last 30 years in adopting a.c. transmission for voltages up to the grid voltage of 132 kV. Alternating current at these voltages is so efficient that I do not think it will be supplanted by direct current. The German Rheinisch-Westfaelisches Elektrizitaetswerk transmission line along the Rhine Valley was designed for 380 000 volts. I saw this line 5 years ago and was told that it was about to be changed over to the full voltage; this has not been done, however, and it is still working at 220 000 volts. I believe the reason is that at 380 000 volts the difficulties associated with alternating current increase much faster than the voltage. It is for these very high voltages, therefore, that d.c. transmission will be of use. I fully agree with the author that the means for doing this will be static apparatus, for both a.c./d.c. and d.c./a.c. conversion. Transformers will be necessary, to be used in conjunction with the valves or rectifiers. We shall see considerable development in this connection before very long. There is plenty of scope for the use of very high-voltage d.c. transmission as an adjunct to, or to supplement, the present British grid. The latter as at present constructed will, however, remain. None of the suggested d.c. schemes will affect the grid, nor is it at all likely that any better technical solution will be invented.

Mr. R. M. Charley: I feel that transmission of electrical power by means of direct current at very high voltages will become an accomplished fact, perhaps to a far greater extent than we imagine at present. In our a.c. systems we largely rely on reactance for protection; I should like to ask the author what will happen under short-circuit conditions on a d.c. system, where reactance is negligible. Perhaps one answer is that the circuit can be interrupted instantaneously by means of grid control on mercury-arc rectifiers. On page 7 it is stated that the proposed voltage for the Norway–Germany transmission is 400 kV for both a.c. and d.c. schemes: I should have thought a much higher voltage would have been suggested for the d.c. alternative. The scheme involves some sea crossings, and perhaps the maximum allowable voltage for a d.c. cable is 200 kV, which means that for 3-wire d.c. transmission 400 kV would be the maximum. If this restriction did not exist, the advantage of the d.c. scheme would be much greater than that indicated in the paper. According to the author the probable limit of d.c. voltage for the present form of mercury-arc rectifier is 30 kV. In view of this, I should like to know what arrangement was assumed for the Norway–Germany scheme where d.c. transmission at 200 kV was proposed. I should like to emphasize that the transvertor developed by Messrs. Highfield and Calverley is worthy of careful consideration in connection with future developments. The author states that the transvertor gives a d.c. voltage which is practically without ripple and that the a.c. wave is almost perfectly sinusoidal. Such a result indicates a favourable comparison with rectifiers. Incidentally, this feature is brought about by the incorporation of the transformer, which is essential for transvertors and rectifiers. Hence we can rest assured that, whatever revolutionary changes from alternating current to direct current for transmission may take place, the transformer will still be required!

Mr. W. Wilson: One of the first of the author's slides showed a Gramme dynamo forming part of a hydro-electric transmission system. I am glad that he mentioned the Gramme machine because I have always considered that it was this which first rendered electrical distribution a practical proposition. In addition to the examples of high-voltage d.c. systems from foreign countries which the author mentions, there are a number of contemporary installations due to British engineers. I described two of these in a paper* published by the Institution in 1916. The first, constructed as early as 1886, included probably the highest-voltage motor which had up till then been installed. The current was generated by two Brush-type d.c. generators, then known as "40-lighters," each developing 10 amperes at 2 kV. These were operated in parallel, with cross-connected fields, and the current was led a distance of 3½ miles to a 6-pole Mordey-Victoria motor taking 20 amperes at 1·6 kV, and developing about 35 h.p. This plant, all of which was manufactured in Lambeth, operated a gold mine effectively until the ore was exhausted after about 12 years' working. I should like to oppose the idea that a.c. transmission is very flexible as compared with d.c. transmission. The reactance of a transmission line is proportional to a constant plus log [(Conductor spacing)/(Conductor radius)]. It is only possible to change this value to a comparatively slight extent by varying either the spacing or thickness of the conductor, and actually every 50-cycle transmission line has a reactance in the vicinity of 0·5 ohm per mile. If a current of 200 amperes is passed through such a line, the IX drop is about 100 volts per mile, and in order that this may not exceed 10 per cent for the whole transmission line the voltage must be at least 1 kV per mile. A.C. transmission lines are therefore much restricted as to their design, since 250 to 300 amperes is the limiting current that a single line can carry, and the voltage must be in the vicinity of the figure I have mentioned. If d.c. transmission were employed, however, there would be no such limitations; the amount of current carried by a line would be limited only by heating and IR drop considerations, and the voltage would only need to be high enough to meet these conditions. I am disappointed to find from the Table on page 7 that the saving to be obtained by the adoption of d.c. transmission in comparison with the other three systems tabulated only amounts to 5 per cent. The author puts up such a good case for d.c. working that I feel certain there must be something wrong with this figure. So small a gain would not render it worth while to give up the advantages which alternating current still possesses over direct current, such as the ability to use current transformers for metering and protective gear. The paper contains a number of examples of super-power projects making use of d.c. transmission. Years ago, when the Victoria Falls Co. was first formed, it was proposed to take d.c. power from a hydro-electric station at the Falls and transmit it a distance of about 700 miles to the south. It would be interesting if the author would include in his reply a description of this scheme, and the reasons for its abandonment.

Mr. A. T. Bartlett: I have a firm belief that extra-high-tension d.c. transmission will be adopted in the future, and that the many difficulties ahead of it will be overcome with the expenditure of money and effort. I am rather surprised that the historical part of the paper makes no mention of Lord Kelvin, who, when chairman of the Niagara Commission, remained to the last entirely opposed to the use of an a.c. scheme in any shape or form. The paper describes several very large projected schemes covering nearly the whole of Europe. Mention is continually made of transmission of power in one direction only, which in theory is relatively easy. If it is necessary to transmit power in the reverse direction, however, the scheme becomes very much more difficult. In presenting his paper the author gave a very clear description of the Marx rectifier, but he omitted to mention that, unlike the mercury-vapour rectifier, this device has no inherent non-return valve action. By suitably adjusting the ignition spark of the Marx rectifier one can pass either the positive or the negative halves of the waves, and it seems to me that the possibility of changing over the transmission of power from one direction to another by so simple a means renders the Marx rectifier the most suitable type where reversal of power is necessary. As regards actual accomplishment, the results of experiments made with the Marx rectifier at the Zschornewitz station near Berlin, where a single-phase output of 90 kVA and 76 amperes was achieved, far exceed those obtained from any other type of rectifier.

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* *Journal I.E.E.*, 1916, vol. 54, p. 276.

Mr. H. S. Davidson: The author refers to the conversion of existing double-circuit 3-phase 132-kV lines to d.c. operation, and states that the insulation would be sufficient for 185 kV. I suggest that this figure is too high, and that the application of such a voltage would necessitate increasing the flash-over values of insulators now working on 132-kV a.c. lines with earthed neutral point. Will the author state what he considers to be the correct ratio of a.c. to d.c. voltages in relation to the flash-over value of porcelain insulators? To bring about any increase in the flash-over value of insulators on existing transmission lines would be costly and difficult, as in most cases the existing strings could not be lengthened without reducing clearances to earthed metal. A practical point in connection with the suggested conversion is that whereas with two 3-phase lines carried on one tower the circuits are usually arranged one on each side of the tower, and thus one circuit can be made dead for cleaning or other maintenance work while supply is maintained on the other, this important advantage would be lost if such a line were converted to triple-circuit d.c. operation. Has the author any information in connection with the soiling of insulators on the negative conductors of such systems as those to which he refers? It seems to me that such soiling, due to electrical precipitation, would be a serious drawback in the industrial districts of this country, where, even with alternating current, frequent cleaning is required. Finally, can the author say whether interference with wireless-reception and other communication circuits would be increased by the adoption of high-voltage d.c. transmission systems?

Major A. M. Taylor also took part in the discussion. The substance of his remarks is contained in the report of the London discussion (see page 13).

[The author's reply to this discussion will be found on page 31.]

North-Eastern Centre, at Newcastle, 22nd January, 1934.

Mr. F. C. Winfield: In this country we are fortunate in the fact that economical generating sites exist in reasonable proximity to the load centres, so that the transmission of large blocks of power over long distances is not a prime necessity. Even the introduction of the grid system of interconnection between the major stations has not given rise to serious limitations on account of the distances to be covered, and 132-kV 3-phase transmission has proved quite satisfactory. It is possible that should the present loads be quadrupled—and if the present annual rate of increase is continued this may well occur within 15 years—the situation may change somewhat; but even so I feel that the situation can almost certainly be met by extension of the existing 132-kV system with the possible assistance of a few lines working at 250 or 380 kV, which are within the range of present experience. An important factor in this connection is that in this country it is almost impossible to separate transmission entirely from distribution, and the transmission voltage must be kept as low as is reasonable for this purpose. Even for European conditions this point is perhaps worthy of development. Remembering that except where conditions are particularly favourable there is little material difference as between a water-power station and an efficient steam station in the total cost of units generated, the choice between the use of a distant water or steam power station and a local steam station rests purely on the relative costs of transporting energy electrically and in the form of coal. It would seem that before electrical transmission of power over many hundreds of miles can be justified the conditions necessary are very large loads and a complete absence of local fuel at the load point, with a long rail-haulage for coal. I should like to know whether in his investigation of the Norway–Germany scheme Dr. Gosebruch compared the cost of this transmission scheme with one using local generation in Germany. This apart, I feel that we shall not be forced to employ d.c. transmission in England on purely technical grounds, and over here, therefore, it must be judged by the criterion of economy or increased reliability. There appears to be little to be hoped for in pure capital saving, even on the basis of the author's own figures. For an entirely new development such as that shown in Dr. Gosebruch's Table any engineer would require a much greater estimated saving than 5 per cent before accepting the d.c. scheme. The chief possibility for d.c. transmission in this country would therefore seem to lie in changing over the existing grid lines to d.c. operation, thereby securing the advantage of increased capacity of lines without increased expenditure. In this connection I find it difficult to understand the author's comparisons of a.c. and d.c. transmission capacity; my general impression is that he makes out too rosy a case for the latter. On page 3 the author states that a 3-phase double-circuit 132-kV line could be employed as a triple-circuit d.c. line with 370 kV between outers. As the usual assumption is that a d.c. voltage equal to the peak a.c. voltage may be employed on the same insulation, it seems to me that this figure ought to be 215 kV. If so, neglecting skin effect and power factor, for equal amounts of power transmitted the losses for the d.c. case will be half those for the a.c. case, not one-sixth as stated in the paper. Similarly on page 8 the author again assumes that the d.c. voltage to earth may be raised to nearly 2½ times the a.c. voltage to earth. I should be glad to know whether there is any justification for such an assumption, and any practical experience to back it. The paper as a whole appears to skim over the very grave difficulties and uncertainties associated with the problem. It is surely not correct to say that there is a general trend towards the use of direct current for high-voltage transmission. Owing to the difficulties of high-voltage a.c. transmission, considerable interest is being betrayed in the possibility of d.c. transmission, but it will be surprising if d.c. transmission does not bring its own train of special difficulties. For example, a line depending on the use of 128 insulated d.c. generators coupled in series, such as that suggested for the Norway–Germany scheme referred to by the author, is well outside the bounds of present experience and would hardly be faced by any engineer without some general experience on similar lines. Such experience has only been obtained in connection with the Thury system, on much lower voltages than those considered by the author. Similar remarks apply to the alternative scheme using cascaded mercury-arc rectifiers. Has the author any experience of the operation of mercury-arc rectifiers in series, particularly when inverted? How is it proposed to switch these lines? For simple tie lines employing rectifiers, grid control can be employed, and field switching may be resorted to for cascaded generators—although it would seem rather too slow to limit destruction of insulation. Presumably grid-controlled rectifiers would not be used unless normally shunted by switches, which again would make the switching slow. The Norway–Germany scheme incorporates about 2 000 miles of 400-kV line; it would be useless to attempt direct switching on such a gigantic condenser as this represents. Is any experience available of the behaviour of insulator strings operating at d.c. voltages up to 400 kV in fog and dirt conditions? One would anticipate electrolysis and osmosis troubles, and the usual lining-up of the dirt particles. In high-voltage a.c. transmission the number of lightning flash-overs is a small proportion only of the number of lightning disturbances which occur, since the lightning surges will frequently not coincide with the peak of the a.c. voltage. Similar remarks do not apply to d.c. transmission, which would be much more frequently disturbed by lightning flash-overs. While in some respects the d.c. cable presents an easier problem than the a.c. cable, the chief difficulty with regard to high-voltage cables is not hysteresis but ionization. Osmosis troubles may affect the performance of the d.c. cable. There would seem to be a case here for a concentric cable. The author refers to the fact that with d.c. transmission the reactive kVA of the load at the receiving point or points must be provided by local synchronous plant. It is well to point out that a system transmitting 1 million kW, such as the Norway scheme, would require much more than half a million kVA of synchronous plant at the receiving points. He omits to mention that when inverted rectifiers are used a time-controlled synchronous drive must be employed to fix the frequency, or that the wave-shape of the voltage from such inverted rectifiers has not yet been reduced to a form which any engineer would care to put on his system. I do not wish to appear to condemn high-voltage d.c. transmission; in fact I feel that it is a very probable development of the immediate future for special work. I would point out, however, that from the practical engineer's point of view d.c. transmission is still in the academic stage, and much development is necessary before a serious practical application can be justified.

Prof. W. M. Thornton: The schemes described by the author are of the nature of a vast experiment, the economics of which is still speculative. There is no doubt that under certain circumstances high-tension d.c. transmission is feasible. It has been applied both in France and in this country, but economic questions will determine its success or failure. One of the leading arguments in its favour is that it will do away with capacitance current in the strings of suspension insulators. This is an advantage for several reasons; there is in the first place an even distribution of potential along the chain, which eases the situation, for the highest gradient is at the high-tension end of the string where the combination of leakage and capacitance current dries off the surface film of moisture. If the insulators are uniformly wet, it can be shown that the gradient is a straight line. The insulator nearest to the line dries out first, however, because the combination of leakage and capacitance current over the line is greatest there. There is therefore formed at the point of greatest gradient a gap in the leakage path across which there is a discharge which, under normally misty conditions, makes the line noisy. This discharge may, under abnormal conditions of dirt or solid deposit or even of the rate of drying, or possibly as the result of the passage of a transient, cause the whole chain to flash over. There is one special point about the storage of energy in high-tension cables. The amount that soaks in may reach values 100 times greater than the cable would hold if charged to the same potential but with a dielectric constant equal to that found under alternating-current conditions. The cable continues to charge for days, and the charge takes twice the time to escape. At the point of switching off such a line there would be first a heavy spark of the condenser-discharge type. When this is broken by the switch it has a great re-igniting power, so that the piling-up of voltage on the line, due to the residual charge coming out, might and does cause a series of intermittent discharges. The only satisfactory way is to short-circuit the line to earth for several days before handling. I think Prof. Marx's rectifier is a most interesting piece of work, which may open out a new era of high-tension transmission. At the moment I regard it more as a means for tapping a.c. high-tension lines. This is already under consideration. With respect to the transmission of reactive power, if mercury-arc rectifiers are to be used on the receiving end of the line there may be enough ripple in the current to supply all the reactive power needed, for one can obtain a power factor of 0·5 on a unidirectional supply in which there is a large alternating component. Single-phase convertors charging cells can have a power factor as low as this on the d.c. side. In reference to the possibility of difference between the positive and negative strings of insulators as regards the deposit of dirt, we have found that the dirt is deposited equally on positive and negative insulators when they are at the same potential above earth, the insulation of the earthed terminal remaining clean. There should therefore be, as in fact there is, a differing rate of deposit along a string of insulators, the greater rate of deposit being at the high-tension end. The deposit would appear to be proportional to the square of the voltage. We are investigating this point in connection with moisture deposits. Extra-high-tension d.c. transmission lines are not intended for local tapping, and in any case the cost of doing this would be prohibitive. The essence of high-tension transmission is that the power is more valuable at the ends of the network than at intermediate points; otherwise there would be no reason for transmitting to these points.

Mr. R. J. H. Beaty: There are some applications of electric power that can be more efficiently carried out with a supply at constant current than at constant voltage. I should like to ask the author whether the rectifiers described in his paper can be used for working at constant current and variable voltage. On the grounds of reliability, efficiency, and cost, what form of rectifier would he recommend to give a constant direct current of 400 amperes at voltages varying from 60 000 volts to zero, when supplied at constant voltage, 50 cycles per sec., 3-phase? Apparently a transvertor could be built to do this when fed through a constant-current transformer, as was the Ferranti rectifier of the 'nineties, were it not for the compensating windings in the motor stator, but it may be that some other form of compensation could be arranged to meet the case. The limiting figures given for Thury generators are, I think, quite fair. In considering 25 volts per bar one must remember that the field is quite steady and therefore the conditions for commutation are more favourable than they would be in a constant-voltage generator, where the armature reaction fluctuates between wide limits. I have seen a motor-generator on the Oxford system run sparklessly with copper-gauze brushes and 20 volts per bar on the 2 000-volt side. The primary and secondary windings were on one core, and therefore the armature reactions cancelled out and did not affect the field. I should also like to ask the author whether any special difficulties were met with by the Metropolitan Electric Supply Co. in operating their Thury transmission, or whether it was discarded merely in order to unify their system. I do not agree that the efficiency of a large d.c. high-voltage generator would be low, although it might be slightly lower than that of an alternator and rectifier. Owing to the low frequency, the iron loss and the commutator losses would be very low. The only increase would be in the armature end-windings, and as this need not represent a large proportion of the total losses the efficiency should be higher than that of a low-voltage generator. The high-speed alternator has been evolved, not because it is the best machine, but to meet the demands of the steam-turbine designer. It is by no means certain that the steam turbine will always remain our most important prime mover. The Oxford system is handicapped by the low efficiency of its substations if only a small amount of power is to be transformed. A motor-generator of 10 kW output at 2 000/100 volts would have an overall efficiency of about 66 per cent, against 96 per cent for an a.c. transformer of similar output. When we come to deal with powers expressed in megawatts, however, the difference will be less, especially if we include the losses in the devices for counteracting line capacitance. The statement that each case must be considered on its merits is well illustrated by the three examples of proposed schemes described in the paper. In the San José scheme, for instance, the generators, apart from their insulation from earth, would be normal low-voltage machines, whereas in other cases the conditions are entirely different. The experiments with a valve consisting of an arc in compressed air are extremely interesting, and there appear to be possibilities of developing this device into a practical rectifier for the generating end of the line; whatever may be used at the receiving end. Presumably some simple method would be adopted for dealing with the fumes produced. So far as this country is concerned the problem to be solved is not how to transmit more power with existing overhead lines, but how to replace these lines by underground cables.

Mr. P. J. Ryle: In paragraph (iv) on page 3 the author assumes a line insulated for 132 kV alternating current, and suggests that this could be run at 370 kV across the outers on direct current. I should like to know how he arrives at this figure. The a.c. line is insulated to earth for 76·3 kV (r.m.s.), or 108 kV (peak). The d.c. line could therefore only be assumed to run at 216 kV across the outers. For equal total transmitted power, the 3-circuit d.c. line would then have one-half the total loss of the 2-circuit a.c. line, instead of one-sixth of the total loss as suggested by the author. The footnote on page 3 is in my opinion far from clear; perhaps the author would explain the basis on which the statements therein relating to power-transmitting capacity are made. For given conductor size, equal peak voltages to earth, and equal losses, it appears to me that a 6-wire d.c. (i.e. 3-circuit) line could only transmit about 41 per cent more power than a 6-wire (i.e. 2-circuit) a.c. line. I take 6 wires for both, since this is the lowest number on which a true comparison can be made. Turning to the subject of insulation, I should like to refer the author to a letter from Mr. H. M. Barlow* in which doubt is expressed as to whether the conventional multi-unit insulator string as used for alternating current would be satisfactory on direct current. Under a.c. conditions the percentage of the total voltage carried by each unit is practically fixed by the capacitive reactances of the units to each other and to the conductor and other neighbouring metal objects. Under d.c. conditions the capacitance effects would be swamped by the leakage-current drop over the units, which, with fortuitous differences in severity of surface deposit on different units, might seriously upset the voltage distribution over the string. Has the author any records of insulator experience on the Moutiers–Lyons line mentioned on page 2? In the last sentence of the paper he implies that d.c. transmission will be more reliable than a.c. transmission. I think one can say that 95 per cent of faults on a high-voltage a.c. line can be put down to lightning or to fog and deposits on insulators. I cannot see how changing over to direct current is likely to reduce the probability of faults due to either of these causes. The remaining 5 per cent of faults can be put down to defective material or workmanship, gales and blizzards, birds, kite-strings, tree branches, etc., and are obviously independent of the type of supply. Again, how long does the author consider it will be before the rectifying and inverting apparatus becomes as reliable as an ordinary a.c. transformer?

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* *Electrical Times*, 1933, vol. 84, p. 146.

Mr. W. A. A. Burgess: The author entirely overlooks the fault conditions likely to be associated with d.c. transmission. Under normal running conditions one would not expect any oscillatory transients, but in the event of earth faults and flash-overs due to induced voltages the high-voltage d.c. transmission system would surely exhibit every characteristic of a very high-voltage impulse generator. The results of oscillations generated in such a way are likely to be far-reaching, and I am afraid impulse generation would prove to be more the rule than the exception. Prof. Thornton referred to the apparent "soaking" effect associated with d.c. condensers; I have met with evidence of this in the form of very considerable residual charges noticed on a d.c. cable conductor on removing an earth connection which had been firmly bolted to the conductor for a period of at least 12 hours. I should like to ask what is the experience of users of high-voltage d.c. cables in this respect to-day. Although the cables I refer to were of the jute-insulated type operating at 500 volts, and the effect was observed several years ago, it appears that this phenomenon is likely to prove a serious factor in the handling of high-voltage transmission cables. It should be possible considerably to improve the leakage factor for high-voltage d.c. overhead lines by providing discharge rings on both the live conductor and the earth point for every insulator. My experience goes to show that this should result in the precipitation of fog, mist, and dust particles, which would otherwise settle upon the insulator and which are, in a.c. transmission, a considerable factor in the reduction of the insulation margin. Experience upon a number of electrostatic dust and mist precipitators has shown that insulators can be kept clean in this way. It may be of interest to record that it is universal practice to earth the positive side of the circuit rather than the negative, since the voltage at which corona appears is 20 per cent higher when the potential of the live conductor is negative with respect to earth than when it is positive with respect to earth.

Mr. H. V. Field: Can the author confirm that the Marx rectifier will operate inverted? As the discharge can be initiated at any point in the cycle, this is presumably the case. Control of the striking point should also make voltage control possible on the d.c. side. In regard to the inability of d.c. systems to carry reactive power (see page 3), I presume that this question only arises under unbalanced-load conditions of a.c. load, as balanced loads require a constant power input, implying steady current on the d.c. system. The proposed European grid schemes are very interesting, but such schemes would, I consider, be ruled out by considerations of national defence, unless each country installed sufficient generating plant to supply its own requirements, which would possibly increase generating costs. Does the author consider that such d.c. systems will operate as series systems? If so, the above consideration would lead to each country supplying a voltage proportional to its load, and the system could then be split up into a number of smaller schemes without affecting the efficiency or cost, and would give simpler control. Such smaller schemes have distinct possibilities, and would not involve an abnormally large number of generating, rectifying, and inverting units. The switching, control, and metering problems involved would be rather difficult, and would require an appreciable change from present-day practice in a.c. stations. It would be interesting to see what would happen in the vicinity of an open-circuit, due to a line breakage, for example, on a 400-kV d.c. series system.

[The author's reply to this discussion will be found on page 31.]

SCOTTISH CENTRE, AT GLASGOW, 23RD JANUARY, 1934.

Dr. M. G. Say: Until a more suitable system of transformation of energy into the electrical form is found than the present one, which utilizes heteropolar electromagnetic machines, a.c. generation will probably remain, since such machines are by nature producers of alternating e.m.f.'s. On the other hand, transmission concerns the even flow of energy from one place to another, which suggests direct current. There should therefore be no "battle of the systems": electricity should not be looked upon as being either of d.c. *or* a.c. form, but rather of d.c. *and* a.c. form, and of transient, intermittent, pulsating, or any other form as well if it is found desirable. Thus economical and efficient apparatus to convert electrical energy from one form to another is of very great importance. There is no doubt but that for ordinary domestic supply alternating current has many points of advantage, particularly where more complex apparatus such as radio sets is concerned; for here the simple voltage conversion made possible by the transformer is of supreme value. I wish to stress the importance of rectification and converting plant, as this plant frees individual applications of electrical energy from conformity with the system of generation, transmission, or distribution. It seems likely, if the present tendencies continue, that d.c. transmission will come, in America and Europe if not in Britain. It might, however, be as well to anticipate a certain amount of difficulty in its development. Problems of leakage over insulators and on to neighbouring circuits, of osmosis and electrolysis, occur immediately to the mind. I think the author is optimistic in the matter of the "absence of inductance and capacitance," by which he means the effects thereof. On steady loads we might expect these effects to be absent, but transmission is not usually effected at strictly constant loads. The occurrence of sudden load-changes, faults, and switching, will undoubtedly bring these effects into prominence. What effect will the unidirectional electric field have on the semi-mobile dielectric material of cable insulation? Although the author alleges that the transvertor is not defunct, the objections to commutation in air are so great that the grid-controlled rectifier, in which commutation is very advantageously performed in low-pressure mercury vapour, would appear to hold greater promise. If there are definite reasons why it is still considered that the transvertor could be successfully applied to high-voltage d.c. transmission, it would be interesting to know what they are.

Mr. A. F. Stevenson: The author passes over in rather a casual fashion what is the most important part of his paper so far as Britain—and particularly Scotland—is concerned, namely that dealing with cables. Our overhead 132-kV lines in industrial areas cannot be considered satisfactory in the light of experience in foggy weather. To put them underground would entail enormous capital expenditure, whereas the cost of d.c. underground cables, for 132 kV or even higher voltages, would be comparable with the cost of the present lines. D.C. transmission opens up possibilities in regard to the use of homogeneous dielectrics, which are at present barred on account of their high power factor, thereby overcoming the troubles due to the migration of the impregnating material in paper cables.

Mr. G. Henderson: The paper seems to me to be of general interest only to power engineers in this country, for the author's conclusions indicate that high-voltage d.c. transmission will be used as a link between two sources of supply. He mentions that d.c. transmission is not economical below 300 000 volts, for distances of less than 100 miles, and for power values below 100 000 kW. This being so, the possibilities of introducing high-voltage d.c. transmission into this country are extremely remote. Nevertheless, the matter is of interest to manufacturers who may take part in developments of this kind in Europe, the Colonies, or any other countries where large blocks of electrical energy have to be transmitted over long distances. The question of the transmission of reactive power over the transmission lines when fed by rectifiers has been investigated by various authorities on the Continent, and I believe a method has been devised for producing this reactive power. I do not agree with the author that the development of grid-controlled rectifiers has been completed. The development of high-power rectifiers has been slow, and the 16 000-ampere rectifier is still far from perfect. Consider, for example, the possible danger to a grid supply where there are 10 rectifiers in series and the same number in parallel at either end of a transmission line; the supply is always endangered by the fact that any one of the rectifiers is liable to backfire at any time. High-voltage rectifiers will not be thoroughly reliable for some time to come. They have been used only for broadcasting, and are not available for unlimited power and voltage. Fig. 1, which shows transmission lines linking up the whole of Europe and stretching from Sweden to Spain and Italy, is rather optimistic seeing that it is based on the assumption that future wars are unlikely. It is extraordinary that the line is not shown extended into Britain. I have a feeling that a high-tension d.c. transmission system will ultimately be taken under the English Channel and used to sell power to the Continent.

Mr. W. B. Hird: The discussion appears to have wandered from the practical aspect and to have become purely academic. The most important point in the paper has been little referred to, except perhaps by Mr. Henderson. Since power transmission by alternating current is quite satisfactory provided that regulating stations are installed at suitable distances to deal with the reactive losses, the subject of a.c. versus d.c. transmission is reduced to the question whether it will be more economical to erect such stations at intervals of, say, 125 miles along the line to deal only with that small portion of the power which is to be transmitted for longer distances, or whether rectifier stations are to be installed at both ends of the line to deal with the whole of the power generated and used. It is difficult to imagine circumstances where anything more than fractions of the power generated at any one point would require to be transmitted such long distances as to demand several regulating stations, and therefore the cost of these is likely to be always less than that of rectifiers. Until a definite instance is brought forward where the opposite is the case, from the practical point of view it seems rather useless to discuss details of the method of transmission by direct current, however interesting such a discussion may be theoretically.

Major R. Chalmers Black (*communicated*): On a long-distance transmission such as the projected San José tidal power scheme mentioned on page 7 the energy wasted may easily amount to 50 per cent of the total. At a current density of 2 000 amperes per sq. in. the voltage-drop would be practically 120 kV, or 20 per cent, and the daily loss would amount to 14·4 million kWh. Thus only 40 per cent of the units generated would be delivered at Buenos Aires. Even with a load factor of 100 per cent the efficiency of a 700-mile transmission is unlikely to rise above 80 per cent, corresponding to a current density of 2 000 amperes per sq. in. With this may be contrasted the cost of transporting energy in the form of coal over a similar distance of 700 miles. The freight for such a distance may be low as 2s. per ton, corresponding to about 0·007d. per unit on the assumption that 1 800 units are generated from each ton of coal. This works out at about one-tenth the cost per unit of transmitting the power by electrical means. The energy gradient or drop, i.e. the bunker coal expended corresponding to the watts lost in an electrical line, would amount to less than 1 per cent, giving a transmission "efficiency" of over 99 per cent, even allowing for the return voyage being made in ballast. It would appear, therefore, that as a means of transmitting power an electrical line compares most unfavourably with the transporting of the energy in the form of solid fuel or oil. Where the source of power is a variable-flow river, or a tidal power scheme where the power necessarily fluctuates enormously, the costs of electrical transmission will necessarily be somewhat heavy and it will generally prove more economical to use the power locally in the manufacture of some easily transportable product (for example, calcium carbide) which need not necessarily be a fuel. In the case of the Assuan project referred to on page 8 it would be better to carry out the proposed manufacture of fertilizer at Assuan rather than at Cairo, even if this involved carrying part of the raw material to

Assuan. In the case of tidal power schemes within 100 or 200 miles of a prospective load, use might possibly be made of oxygen and hydrogen formed electrolytically from water, the gases being transmitted by separate pipe-lines to various consuming centres. The author enumerates the restrictions in design which limit the output of a commutator dynamo to about 8 000 kW and the maximum voltage (at a very low frequency) to about 10 000 volts. If the conventional design of dynamo is departed from, however, there appears to be no reason why these limits should not be greatly surpassed. If alternator practice is followed and a rotating-field magnet system is adopted, the peripheral speed may be increased to possibly 600 ft. per sec., i.e. to about three times the limiting speed for rotating armatures. The commutator being now stationary and relieved of centrifugal stresses, the commutator speed could be increased somewhat whilst the segment pitch might possibly be still further reduced to 3 mm or less. If, however, the rubbing type of collecting gear is abandoned and the "jump spark" type of collector familiar in motor-car ignition distributors adopted, the speed of collection may be increased to that of the pole tips, i.e. about 600 ft. per sec. The commutator or collector would preferably be formed in two sections, positive and negative, placed one at each end of the stationary armature. The Marx plan of igniting, controlling, and quenching the arcs, which function in place of the usual carbon brushes, could be adapted with some slight modification, giving what would be in effect multiphase (50 or more phases) rectification. The rectifying apparatus would be incorporated in, and would form part of, the generator. These proposed modifications in the design of d.c. dynamos would permit of very material increases in the permissible voltage and/or frequency, and also of the maximum output obtainable. A quite feasible value of 250 volts per commutator segment, the pitch being increased to 25 mm, would permit of 16 kV being dealt with in one armature at 50 cycles per sec., whilst the output could be raised to 22 000 kW at 3 000 r.p.m. Higher values of both voltage and output would be possible at the lower speeds appropriate to large hydraulic turbines operating on low heads. In view of the successful operation of high-speed alternators at 33–35 kV there seems to be no reason why large d.c. generators should not be built capable of dealing with at least 5 000 amperes at 50 kV. Such machines would not differ very greatly from large alternators and could be built of almost any size, running into hundreds of thousands of kilowatts. Ten or twelve such machines would be quite sufficient for even the most grandiose of hydraulic power schemes.

Prof. G. W. O. Howe (*communicated*): The trend of development during the last 30 years had appeared to establish a.c. transmission as the only method to be seriously considered, and one had come to regard the pioneer work of Thury as being now only of "museum" interest. The paper proves conclusively, however, that the battle between direct current and alternating current for long-distance transmission has yet to be fought. In discussing the relative merits of the two systems there is a danger of overlooking the fact that the disadvantages of a.c. transmission are known whereas those of d.c. transmission have yet to be discovered. It is easy to carry out calculations based on a 370-kV d.c. line with earthed neutral, but such a system may not behave so well as its advocates assume. It is known that moisture is attracted to conductors at a negative potential, and osmosis may prove a very serious enemy to the insulation of conductors at a negative potential of 185 000 volts. There can be no doubt of the advantage of eliminating the effects of inductance and capacitance. To realize how surprising these effects can be one has only to consider the case of a 140 000-volt 3-phase line 300 miles long; the current at the sending end of the line is greater when the receiving end is open than when it is loaded with 20 000 kW. The fact that the working voltage of a d.c. transmission line is continuous and does not rise to 1·4 times its r.m.s. value 100 times per second has its advantages, but, as I have already indicated, I am not sure that it will all be quite so simple as the arithmetic promises. A string of insulators distributes the a.c. voltage among the units according to their relative capacitances. With direct current, however, distribution would be governed not by capacitance but by leakage, a very much less definite factor, especially in view of the action of moisture to which I have referred. With regard to skin effect, which the author picturesquely ascribes to gravity, the magnitude of the effect is hardly sufficient to make it a factor of any importance. A solid copper conductor 1 inch diameter at a frequency of 50 has a resistance about 7 per cent higher than its d.c. value. For an aluminium conductor the figure is still less. If hollow conductors are employed so that the diameter is large enough to prevent excessive loss due to corona, the effect is still further reduced. Compared with the other disadvantages of a.c. transmission, skin effect may be neglected. There is one sentence in the paper which I should like the author to expand. He concludes Section (2) by saying "there is the problem arising from the inability of a direct-current transmission line to carry reactive power." Reactive power, so-called, is no power at all, and, if we obey instructions, we no longer measure it in watts but in vars. The d.c. transmission line transmits watts and knows nothing of vars, and if vars are wanted at the far end—as they will be for producing alternating magnetic fields—then they will have to be made for the purpose at that end.

[The author's reply to this discussion will be found on page 31.]

WEST WALES (SWANSEA) SUB-CENTRE, AT SWANSEA, 22ND FEBRUARY, 1934.

Mr. G. O. James: I am doubtful whether the suggestion of joining two large a.c. systems by a d.c. transmission line would provide a reliable means of interconnection. Would the converting equipment be flexible enough to deal with the fluctuations of load? I do not think it would be an economic proposition to tap the high-tension d.c. network at intermediate places to supply relatively small loads. Furthermore, the transformer has a decided advantage over rectifying plant in regard to simplicity, efficiency, and flexibility.

The cost of rectifying plant and of the attention and maintenance required might outbalance the saving obtained in transmission losses. The main difficulty seems to be that of metering on the d.c. high-tension side; how is it intended that this should be carried out? Electrolysis would probably play a large part in the creation of practical problems.

Mr. R. G. Isaacs: Although we are unlikely to require high-voltage d.c. transmission in this country, the importance of the paper can be seen from Section (5), particularly schemes (*b*) and (*c*), in which it is to be hoped that British engineers will have a share. Most of the items in the author's list of advantages of d.c. transmission fall into insignificance in comparison with the saving in conductor material. In this connection, the basis of the calculation on page 8 is not clear. Is not the insulation to earth only sufficient for $185/\sqrt{3}$ kV? In view of the fact that the mercury-arc convertor and invertor appear to provide a neat solution of the problem, it is disappointing to find that the author thinks this solution is ruled out for high-voltage high-power schemes. In forming this opinion, have the possibilities of shielding grids been taken into account?

Mr. R. H. Davidge: Instability is noticeable in a.c. ring mains even of small dimensions, say 20 to 30 miles in length, especially when they are connected to points of supply which have variable load characteristics, such as collieries and rolling-mills. Does the author think it will be necessary, in the course of time, to employ d.c. transmission in order to maintain stability of the grid transmission scheme?

Mr. A. Cross: It would be interesting to know the manner in which it is proposed to carry out the inversion process from high-tension direct current to 50-cycle alternating current. A likely method which occurs to me is to apply a low-voltage 50-cycle excitation to the grids of the mercury-vapour rectifiers and utilize the primary of the high-tension a.c. transformer feeding the a.c. transmission lines as the load impedance for the mercury-vapour rectifier.

[The author's reply to this discussion will be found on page 31.]

EAST MIDLAND SUB-CENTRE, AT LOUGHBOROUGH, 27TH FEBRUARY, 1934.

Mr. M. J. Mortimer: I recently had the pleasure of witnessing a demonstration of the grid-controlled mercury rectifier. The experiments showed the conversion of alternating current to direct current, of direct current to alternating current, and also of one frequency of alternating current to a different frequency. When I came away it appeared to me that some of the grid substations were doomed before they were put into commission. I realize now, however, that the matter is not quite so serious as this, because, according to the author, our present 3-phase a.c. 132-kV grid system can be satisfactorily worked provided we have suitable balancing stations at intervals of about 100 miles. It appears that the solution of the problem of e.h.t. direct-current transmission will be found in the direction of large rectifiers working at high voltages, and until we get these we cannot go very far along the lines described by the author. He gives us to understand that transport considerations limit mercury-arc rectifiers to about 8 000 kW capacity, a very low figure in these days. Would it be possible to build the rectifier on the site it has to occupy? Whether we shall see a d.c. system of 300 000 volts operating in this country within the next 20 years is very doubtful. The consumer will have to pay off the capital charges outstanding on the grid before we can alter the situation.

Mr. G. Smith: I notice that the paper mentions " skin effect at high voltages "; should this not read " skin effect with heavy currents "? It should be remembered that the skin effect is greater with large currents and large-diameter conductors. Further, where steel-cored aluminium cables are used for long spans, the result of the skin effect is chiefly to cause the current to be carried by the aluminium strands rather than by the steel core. I should like the author to say how he would eliminate ripples from the d.c. lines, as the use of chokes and condensers would be very expensive. Have the effects of electrolytic action due to leakage currents been considered? On a d.c. system serious trouble might arise owing to terminals and fittings being eaten away electrolytically. The effects of a flash-over or a short-circuit on a d.c. system would be much worse than on an a.c. system, and it would be interesting to learn how adequate protection and isolation of d.c. transmission lines could be obtained.

Mr. J. S. Messent: The paper represents a thorough exploration of what would happen under d.c. transmission conditions if we had the necessary means of rectification and inversion, which have, however, not yet been developed. A few years ago the author of a paper* on the Norway–Germany project emphasized that the equipment for the scheme did not exist; no doubt its accomplishment is nearer now. I suggest that there is no scope for d.c. transmission in the British Isles, because there are no two places remote from each other where the costs of generation differ so greatly as to warrant transmission of large blocks of power.

Mr. J. F. Driver: The subject of high-tension transmission of power by direct current should interest Loughborough engineers because Brush was the first man to transmit high-tension direct current. It would be interesting to know whether generators built on the lines of the old Brush generator might lead to a solution of the problem. The probability is that the solution will be the generation of alternating current, its conversion to direct current, and then the inversion of the latter to alternating current. This last stage presents an exceedingly difficult problem, except when some mechanical system of inversion on the lines of the Highfield booster is employed. I gather from the paper that the mercury-arc rectifier is not likely to be a success beyond a comparatively low d.c. voltage: I should like to ask whether it is possible to run a number of such rectifiers in series. It would be interesting to know how such apparatus runs in parallel, and how it would behave at the voltages mentioned by the author. What would be the magnitude of the current caused by a short-circuit on a 400 000-volt d.c. system? This question leads us to the problem of circuit breakers for a super-tension d.c. system. I suggest that the most serious problem that would arise on such a system would be the provision of suitable insulators. Those which we use at present would probably not be satisfactory. I very much doubt whether a 180 000-volt a.c. line could be converted into a 400 000-volt d.c. line; in my opinion the design of the insulators would have to be altered. Certain of the insulators would quickly get dirty, the speed depending upon the nature of the dust found in the particular neighbourhood. I have performed a number of experiments on the electrostatic field round insulators, and have found that the effects of direct current and of alternating current are very distinct. The smoking-up of the insulators would be a very serious problem on a high-tension d.c. transmission system. I think the most important of the author's points is the question of the instability of an a.c. line. He makes it very clear that this is probably the limiting factor governing the length of the line; but whatever its length it can always be provided with intermediate substations. I should like to ask the author what are the commercial possibilities of inverting to alternating current, so as to enable the direct current to be used economically at the end of a long line.

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* See Bibliography, (14), on page 9.

Mr. C. A. Brearley: In high-voltage d.c. cables, is there any tendency to oil osmosis, i.e. the driving of oil from one pole to the other? If so, would the provision of oil ducts both at the centre and underneath the lead sheath be a practicable method of dealing with the trouble? I should like to know whether the relation of the a.c. voltage to the d.c. voltage cited in Section 2(iv) is based on operating conditions. It seems to me that a steady voltage in one direction might tend, especially when the insulators were dirty, to create a leakage path over the insulators which would be as sensitive to flash-over as that associated with an alternating voltage. Does the steady nature of the line voltage in the case of direct current at a potential between the potentials of a cloud and the earth encourage a direct lightning stroke? Is the transvertor referred to in Section 4(*a*) substantially free from higher harmonics, so that in the conversion from direct current to alternating current the expense of a filter circuit will be relatively low? The author mentions that road and railway loading gauges mark one of the limitations in the permissible size of steel-tank rectifiers; is a flat half-moon shape for the rectifier feasible, with the electrodes arranged in circular arcs in, say, two vertical planes?

Mr. F. W. G. Osborne: The paper demonstrates that d.c. transmission is essentially a high-voltage proposition, and as it is the trend of the present day to employ 3-phase 4-wire distribution none of the objections made by the author to alternating current will worry the engineer who is interested in getting electricity from the substations to the consumers. We cannot continue indefinitely to increase the capital cost of the distribution of electricity by scrapping one distribution system every 50 years and building up another.

Mr. F. G. McDonald: Is there any reason why we could not use a mercury-arc rectifier, and, instead of transmitting direct current, transmit very low-frequency alternating current, transforming the latter at either end?

Mr. M. B. Wilson: I should like to know whether the author has any data on which he bases his ideas, and costs, of direct current, as compared with alternating current, for a given length of line and a given voltage. Also, is there any object in the change-over to direct current in this country?

[The author's reply to this discussion will be found on page 31.]

North Midland Centre, at Leeds, 6th March, 1934.

Prof. E. L. E. Wheatcroft: In discussing the matter of d.c. transmission we are putting the cart before the horse, the "horse" in this case being the invertor—the plant for converting from direct to alternating current. That such plant will be needed goes without saying, since high-voltage direct current is unsuitable for distribution. We must bear in mind the scale of the problem. It is not likely that d.c. transmission will be considered except for hundreds of thousands or even millions of kilowatts, and, since the transmission distances will be great, 200, 300, or 400 kV will be required for economic operation.

The load which the invertor must eventually supply is an ordinary distribution load of lagging power factor. Thus there will necessarily be inductance in the load circuit, and there will also be a high inductance in the transmission line: for unless the line is so long that this condition is satisfied there will be no economic reason for resorting to direct current. The invertor is an apparatus designed for switching or commutating. In essence, therefore, it does no more than a reversing switch does. Now a reversal can be caused either by the circuit being opened in the process of re-connecting or by short-circuiting. It is clear that for transmission purposes, where there is a high inductance on the d.c. side, the process of transition must be a short-circuit. Fig. E shows what would take place if the invertor alone were installed: diagram (*a*) shows the conditions just before reversal, and (*b*) shows the transition stage when both sides are temporarily short-circuited. During the transition period the current continues to flow on both sides on account of their respective inductances. Diagram (*c*)

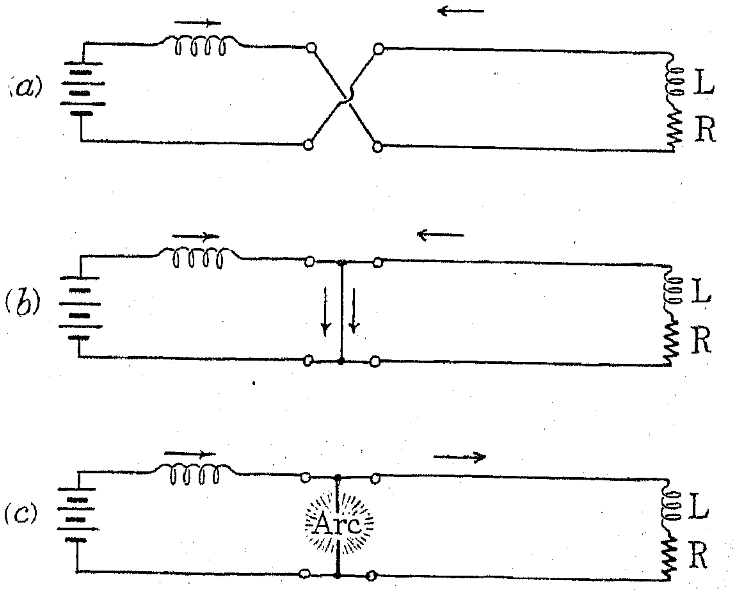

Fig. E.

shows the process of commutation, and it will be seen that this can only be achieved by interrupting the current in the short-circuiting connection. This must obviously result in a dissipation of the stored magnetic energy in a power arc. The lengths of the arrows in Fig. E are a measure of the magnitudes of the currents at the instants corresponding to stages (*a*), (*b*), and (*c*). Fig. F shows the case where there is synchronous machinery available to perform the commutation and supply the "magnetizing current" to the load. Each of the angles indicated on the left-hand side represents an instant in the half-cycle. From 0° to 30° the sudden rise of current in the short-circuited machine effects the commutation, i.e. the reversal of current in the invertor itself; for the remainder of the half-cycle the machine is engaged in reversing the current in the load. No power need now be lost in switching. I have endeavoured to show that synchronous machinery, or some other apparatus for effecting a temporary storage of energy, is essential to inversion plant. Quantitatively, with a 70 per cent power-factor load, the condenser kVA will probably need to be about 1·5 times the load kW. I have emphasized these points in order to show that the invertor is really the most important part of the problem of d.c. transmission. I should like the author to complete his survey of the subject and make its perspective more correct by considering this problem of inversion. There are two possible solutions. One will be achieved by the rotating-commutator type of plant, which will operate with the synchronous machinery suggested in the diagrams; the other will make use of controlled-arc devices, operating in conjunction with static condensers to provide the necessary storage of energy for the reversal of the current.

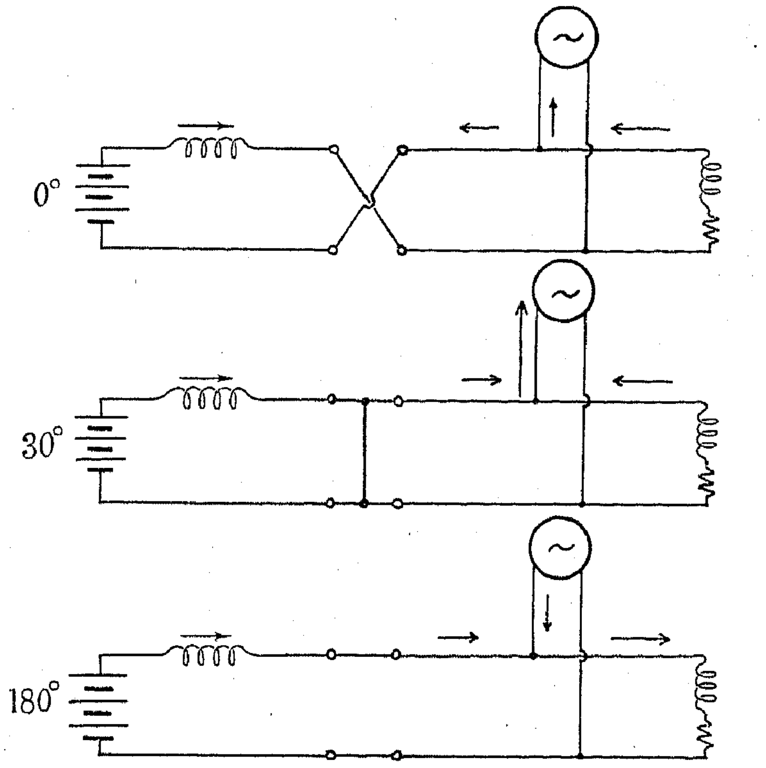

FIG. F.

Mr. W. T. J. Atkins: We in this country can only have an impersonal interest in the matter of d.c. transmission, because it is only justifiable for the transmission of very large blocks of power over great distances. There is, however, an alternative method which involves quite a number of the advantages enumerated in the paper, but is applicable under conditions existing in this country. I refer to the use of the series system with alternating current, and in fact with 3-phase alternating current. Such a method of transmission would secure stability of the system and immunity from shock due to faults. Suppose there are a number of single-phase generating stations, and that they are ringed together by a single conductor: this represents a single-phase simplified version of the system I am attempting to describe. Each of these stations will be connected with the ring conductor through a series transformer rather similar to a booster, and the series-transformer winding on the station side will be connected to the station through one or other of the known devices for converting from the "constant current" to the "constant potential" system. It is quite possible to extend the idea to 3-phase working by having, instead of one conductor, three conductors in the ring. The individual stations will continue to work with 3-phase alternating current at constant potential, and the ring main will work with constant current, the voltage depending on the load being transmitted. Each conductor in such a ring-main system may be entirely isolated from the other two, and any faults which may occur—either to earth or between conductors—are entirely without effect on the working of the system. (In practice it might be desirable to install compensating reactances on the lines of Petersen coils.) An advantage of such an arrangement is that faults on the individual systems connected in this manner will be, for practical purposes, without effect on the other systems. Since load in a constant-potential system is measured by current and in a constant-current system is measured by potential, a fault condition will draw from the booster transformer a correspondingly large current. This will tend to be converted to a correspondingly large potential in the transformer, but, if the latter is designed in the way most transformers are designed, saturation will occur, with the result that the voltage will not rise to more than about twice the normal value. The effect of such a condition when reflected into the other systems is therefore negligible in amount. An open circuit on the ring main will, of course, be of serious consequence, but it is by no means impossible to devise safeguards, and in any case such an eventuality is extremely unlikely. Switchgear can be designed to work with this system by short-circuiting the components, and would be extremely simple and cheap. The 3-phase transformer for converting from constant potential to constant current presents no difficulty, methods for carrying out this operation having been described by Steinmetz and others. There are some difficulties, however, such as power-factor limitations, and the cost and general distrust on the part of engineers of the static condensers forming part of the conversion equipment. Also, there is the standing loss due to the constant current in the transmission line and series transformers. As the author points out, however, in connection with the Thury direct-current system, means could be devised for decreasing the current at times of light load, and so overcoming to some extent this objection.

Mr. W. E. French: With reference to the high-tension direct-current generators of the Thury system, the author gives (page 4) the voltage formula $V = ev_c/(2fs)$, whereas I always use $V = ev_c/(\pi fs)$.

Will he please explain how the factor "2" is obtained? These values are of importance since they affect the maximum speeds attainable. They also affect the problem of "ringfire" and ultimate flash-over, which must be carefully considered with such high-voltage machines. The relation which governs ringfire and flash-over in d.c. machines is:[*]

$$D \geq 2t\frac{p}{a} \cdot \frac{100\pi(\text{kVA})}{d_i(\text{AC})e} \text{ cm}$$

Accepting the author's figures, namely 300 r.p.m., $e = 25$ volts, 8 000 kW (or kVA), $\text{AC} = q = 550$, the minimum diameter for prevention of flash-over is $D = 510$ cm $= 16$ ft. The corresponding armature peripheral speed is $v_a = 80$ m per sec. Hence, obviously, the peripheral armature speed given, namely, $v_a = 59$ m per sec., will not correspond to a machine diameter which may be assumed to be reliable from the point of view of flash-over. If the factor π be used instead of 2, then the speeds are reduced to 210 and 265 r.p.m. respectively. Taking 265 r.p.m., the diameter is $D = 430$ cm $= 14$ ft., i.e. much below the safe limit for flash-over. It will thus be seen that the factors π and 2 have an important bearing on the Thury system limits. Next as regards the transvertor, in normal d.c. machines the voltage between segments may be 25 to 30 with commutating poles, and from 35 to 40 volts may possibly be used when the machine is supplied with commutating poles and compensatory windings which eliminate distortion of the main field, so that $e = e_{max.}$. The limiting value of e is determined by the voltage which bridges the small insulation between the commutator segments, thus setting up a small arc which initiates ringfire and ultimate flash-over. Since in the transvertor the insulation between segments is air and the intersegmental space is relatively large, the limiting voltage can be increased to $e = 160$ volts, and even more. Further, it appears that compensation from the synchronous motor is sufficiently effective to prevent any serious increase in e, so that flash-over is unlikely to occur. The main difficulty appears to lie in the actual commutation when the transformer sections between the commutator segments are short-circuited by the brushes. The reactance voltage is not constant over the commutation period and, in order to neutralize it, the compensating voltage must follow the same law. If this cannot be accomplished, considerable sparking voltages arise at the end of the commutation period, causing heavy sparking at the trailing-brush tips. In commutating-pole machines the compensating-voltage curve can be adjusted with considerable accuracy to that of the reactance voltage, and the commutation process is well under control. So far as I am able to judge, in spite of the various attempts at compensation—of which there are quite a number, apart from the synchronous-motor compensation mentioned by the author—it must be extremely difficult, if not impossible, to obtain sufficiently good agreement between the reactance and compensating voltages for good commutation. In short, the commutation in the d.c. machine is a controlled process and in the transvertor an uncontrolled one. To this must be added the considerable practical difficulties of insulating rotating brush-gear at high voltages, and the maintenance of perfect centring of the stationary commutator. Finally, when considering high-tension d.c. transmission by means of rectifiers and invertors, and taking inversion as an energy return from d.c. to a.c. systems, inversion can be effected in two ways: (1) by a voltage reversal, and (2) by a current reversal. In the mercury-arc apparatus current can only flow in one direction, and therefore inversion must be by voltage reversal. This implies that the voltage of the half wave during which the anode current flows on rectification must be suppressed and delayed 180° (electrical) by a negative grid potential, so that in all cases currents flow in opposition to the alternating potentials; therefore, in order to change over from rectification to inversion, the brush gear of the grid-control mechanism has to be moved by 180° (electrical). In the mercury jet-wave apparatus[*] inversion is due to current reversal and occurs perfectly naturally and automatically when the voltage of the d.c. system is greater than that of the a.c. system, and the apparatus returns as smoothly to rectification when the voltage of the a.c. system is higher than that of the d.c. system. The commutation of the jet-wave apparatus is even more favourable on rectification than on inversion.[†] With the mercury-arc apparatus, change-over either from rectification to inversion, or from inversion to rectification, necessitates the reversal of the mains as well as of the brush position of the grid-control mechanism, as explained above. Inversion by the mercury jet-wave apparatus may thus be considered to be a perfectly natural event, whereas inversion by the mercury arc is a forced process. Thus, when interlinking a.c. systems by means of high-tension d.c. transmission, the mercury jet-wave will constitute a far superior and elastic link as regards energy exchange between the linked a.c. systems.

Mr. B. D. Youatt: The author advocates d.c. transmission on the grounds that we are approaching the limit of alternating current for the transfer of large blocks of power over considerable distances; but is direct current the only alternative? I suggest that a broader view should be taken. We have long been accustomed to look on electricity as a versatile and flexible commodity applicable to almost any industrial process or domestic need. It does not follow that it is necessarily the best way to transmit large blocks of power over long distances. Prof. Marchant has shown[‡] that even the comparatively crude method of carting coal is competitive. In Germany another method is meeting with some success, the medium being hydrogen gas. It is produced electrolytically, and transmitted through pipes of fine bore and, to withstand the enormous pressures, of considerable wall thickness. Has the author considered these and other possible alternatives to either a.c. or d.c. transmission?

Mr. J. N. Waite: This country is unique in that all its great load centres are located either on, or immediately adjacent to, coal-fields. It is obviously useless to transmit power from one coal-field to another, but this point is often lost sight of by transmission engineers.

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[*] See Arnold: "Gleichstrommaschine," vol. 2.

[*] See J. Hartmann: *Journal I.E.E.*, 1930, vol. 68, p. 945, and also W. E. French: *Electrical Review*, 1933, vol. 113, p. 655.

[†] *Journal I.E.E.*, 1930, vol. 68, p. 984.

[‡] Report of the British Association, 1929, p. 365.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, MANCHESTER, BIRMINGHAM, NEWCASTLE, GLASGOW, SWANSEA, LOUGHBOROUGH, AND LEEDS.

Mr. H. Rissik (*in reply*): The wealth and variety of discussion accorded to the paper, and, in particular, the practical nature of the many contributions to that discussion, indicate only too clearly that the paper has been of more than academic interest. It is, of course, quite true, as many speakers have pointed out, that having regard to the purpose of the British grid the adoption of any system of high-tension direct-current transmission in this island has no justification whatsoever, either in practice or even in theory. So that in this rather narrow sense the subject in question may perhaps be regarded as being of academic interest only to electrical engineers in this country. Taking a broader, less insular view, however, and remembering the part that Great Britain has played in the development abroad of electric power and its utilization, it is fitting that we should continue to look ahead, and consider seriously the possibilities of an alternative system of transmitting electrical energy which has many actual—and not a few latent—advantages over the system hitherto prevailing. It is perhaps scarcely necessary to point out that in the United States of America, where the interconnection of large high-voltage power systems is the order of the day, difficulties inherent in the use of alternating current are already being experienced; and that in the U.S.S.R., where the development of electric power and its use on a large scale is only now being attempted, investigations are at this moment proceeding with a view to the adoption of long-distance transmission svstems operating with high-tension direct current.

I propose to group my replies to the various contributors to the discussion according to the subject matter of their remarks.

Insulation.

A large number of speakers, notably Mr. Beard (London), Messrs. Romero and Farrer (Manchester), Mr. Davidson (Birmingham), Messrs. Winfield and Ryle (Newcastle), and Mr. Isaacs (Swansea), have challenged my figure for the safe d.c. voltage to earth equivalent to a given a.c. voltage to earth. Mr. Beard questions even the conservative ratio of $\sqrt{2}:1$, whereas on page 8 I have employed a ratio as high as $185:132/\sqrt{3} = 2 \cdot 4:1$. Admittedly the data at present available are somewhat scanty, yet experience with the Moutiers-Lyons system goes to show that the permissible equivalent d.c. voltage is much more than 40 per cent higher, and even more than 100 per cent higher, than the a.c. voltage to earth. Mr. W. E. Highfield mentions, in his opening remarks before the Institution, 40-kV alternating-current cables operating satisfactorily as 100-kV direct-current cables. Whilst elsewhere* Mr. J. S. Highfield has given instances of tests on insulators where an "equivalent" voltage-ratio of over 3 : 1 was obtained, the average value of this ratio lying between 2 : 1 and $2\frac{1}{2}:1$. At the same time I am in agreement with Mr. Beard that a comprehensive investigation of the comparative flash-over values of insulator strings on alternating current and on direct current is essential before any very large scheme of direct-current transmission is embarked upon.

Economic Comparisons.

Mr. Wilson (Birmingham) expresses his disappointment that the table given on page 7 shows an estimated financial saving of only 5 per cent in favour of the direct-current system in the case of the projected Norway–Germany transmission scheme. Mr. Beard (London) and Mr. Winfield (Newcastle) both regard this saving as being at best somewhat problematical, whilst Mr. Young (London) goes further in maintaining that its magnitude indicates that there is little evidence at the moment to justify my final paragraph. The main reason for the small financial saving in favour of the high-tension d.c. scheme is that the same transmission voltage, namely 410 kV, was assumed in both cases. As the result, the losses became 62 per cent higher in the d.c. case. It seems doubtful whether in the present state of the art 410 kV can be considered a practicable transmission voltage for alternating-current working. Assuming a lower transmission voltage, and thus the same transmission losses as in the d.c. case, the annual saving in favour of the high-tension d.c. scheme would be augmented to 33 per cent.

Static Current-Converting Apparatus.

Undoubtedly, much research coupled with extensive field tests is necessary before the mercury-arc rectifier can be applied to the conversion of alternating current to direct current, and more particularly to the inversion of direct current to alternating current at pressures of the order of 100 000 volts. I am indebted to Prof. Wheatcroft (Leeds) for his lucid exposition of the inversion problem, wherein he shows the necessity for synchronous machinery at the receiving end momentarily to store the magnetic energy in the inductive elements of the invertor unit. It is therefore clear, as I have pointed out, that a high-tension d.c. transmission line can only act as a power link between a.c. networks which individually supply their own requirements as to reactive kVA.

Dr. Thompson (London) mentions the arrangement of several mercury-arc discharge devices, proposed by Dr. Petersen for overcoming the inability of the invertor to supply reactive kVA in addition to active kW. I am not, however, convinced that this particular solution is correct in theory; it appears to be based on the assumption that the sum of the instantaneous reactive components of the alternating currents in a symmetrical 3-phase system is always zero. At any rate, no practical form of Dr. Petersen's special invertor connection has as yet made its appearance, whilst almost nothing has been published regarding the theory of its operation.

As far as the straightforward mercury-arc invertor is concerned, this type of apparatus is at present operating successfully in Italy in connection with regenerative working on a 3 300-volt d.c. traction system. I believe that such "reversible" rectifier substations are also being installed on the South African railways.

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* *Journal I.E.E.*, 1912, vol. 49, p. 848.

Load Switching.

Several contributors to the discussion before the Institution, including Mr. Ayres and Mr. Taylor, raise the question of switchgear for a high-tension d.c. transmission line. The fact that such switchgear is not required constitutes an important advantage in favour of the d.c. system. As is well known, the rectifier can be made to operate as its own circuit breaker in that the flow of energy from the a.c. side to the d.c. side—and vice versa in the case of an invertor—can be completely and decisively interrupted merely by applying a suitable negative potential to certain control grids located in the discharge path. This method of load switching can, of course, be adopted also in the case of a tee-off. Mr. Ayres wonders what happens when a power flow measured in millions of kilowatts is suddenly interrupted; but such a question can only be of academic interest. It is customary in practice to switch out sections of the load, so that a 40 000-kW rectifier unit, for example, would only have to dissipate some 400 kW-sec. in the half-cycle necessary for complete extinction of the arc—by no means an impossible task when one remembers that modern oil switches successfully dissipate 1 000 kW-sec. and more during 3 or 4 cycles.

Short-Circuit Protection.

Many speakers, in alluding to the difficulty of protecting a d.c. system against short-circuits and other electrical disturbances, overlook the fact that in such a system large reactors can be introduced to give "buffer" protection without in any way affecting the economic operation of the system. The only loss associated with the inclusion of reactance in a d.c. system is the copper loss in the reactors. For this reason this method of protection is universally employed in the supply of high-tension direct current to the transmitting valves of modern broadcasting stations, whether that supply be obtained from rectifiers or from d.c. generators.

Interference Due to Harmonics.

Mr. Davidson (Birmingham) and Mr. Smith (Loughborough) inquire as to the likelihood of interference with communication circuits arising from the harmonics generated by the rectifier. This matter is also referred to by Mr. Highfield (London). The reasons for the generation of these harmonics, and their magnitudes in certain circumstances, have been dealt with fully in an earlier paper.* These harmonics can be almost entirely eliminated by sufficient phase multiplication, which is not a difficult question in the case of large converting units. In the 1 000-kW transvertor exhibited at Wembley in 1924, 36 secondary phases were employed, giving a rectilinear output voltage and a practically sinusoidal input current.

Design of High-Voltage Direct-Current Generators.

Replying to Mr. French (Leeds), the formula given on page 4 for the limiting voltage V is derived from the following equations relating to the voltage per segment e, the pitch of the commutator segments s, the magnetic frequency f, and the peripheral speed of the commutator v_c:—

$$e = \frac{V}{z/(2p)}; \quad s = \frac{\pi D_c}{z}; \quad f = \frac{np}{60}; \quad v_c = \frac{\pi D_c n}{60}$$

where p = number of pole pairs, z = number of commutator segments, D_c = diameter of commutator, and n = speed in r.p.m.

As far as the transvertor is concerned, I do not agree that commutation is an "uncontrolled" process, as Mr. French suggests. On the contrary, the methods perfected by Mr. Calverley since the exhibition of the 1 000-kW machine at Wembley in 1924 have completely overcome the commutation difficulty, in that proper compensation of the various harmonic voltages is now effected in the transformer element of the machine. Details of the method are given in Mr. Calverley's later papers on the subject.*

Miscellaneous.

Replying to the query of Mr. Wilson (Birmingham) regarding the abandonment of direct current for the Victoria Falls scheme, this was occasioned by the discovery of coal on the Rand, so that the necessity for transmitting electrical energy from the Falls no longer arose.

Mr. Beaty (Newcastle) raises the interesting question of the possibility of a constant-current system using grid-controlled rectifiers. Such an arrangement would be ideal from the point of view of rectifier operation, but the low power factor on the a.c. side occurring at periods of light load (and thus of low d.c. voltage) would appear to be a very serious drawback.

In reply to Mr. Field (Newcastle), the Marx rectifier has been shown to operate satisfactorily as an invertor in the electrical laboratory stage of its development, but I am unaware of any success in this direction as far as commercial units are concerned.

Replying to Mr. McDonald (Loughborough), there is no technical reason why mercury-arc frequency-convertors could not be used in conjunction with a low-frequency system of a.c. transmission. Such a system would scarcely be economic because of the cost of, and losses in, additional transformers on the low-frequency side. At the same time it is not yet certain whether the static frequency-convertor is such a reliable piece of apparatus, under conditions of varying load and power factor, as the mercury-arc rectifier. I believe that a considerable amount of research work is at the moment being carried out in Germany with a view to the bulk conversion of 3-phase current at 50 cycles per sec. to single-phase current at 16$\frac{2}{3}$ cycles per sec. for supplying a.c. traction systems.

I would refer Mr. Page (London) to the description of the Glesum system, developed by von Platen, given in the communication from Col. Crompton (London).

Mr. Taylour (Birmingham) has perhaps taken my statement regarding the limiting size and voltage of mercury-arc rectifiers somewhat too literally. The figures given on page 5 relate to the state of the art at the time of reading of the paper, and are not meant to stand as an indictment of the ingenuity of rectifier designers. I intended to convey that, at the present day, steel-tank rectifiers delivering 10 000 kW at 30 kV cannot be considered to be a commercial proposition. On the other hand, several manufacturers would be prepared to tender for, say, a 1 000 kW unit operating at 30 kV and, possibly, even 50 kV. Mr. Taylour is quite right in stating that no serious effort has as yet been made to adapt existing designs to high-voltage working. He is inclined to forget, however, that such efforts cost a great deal of money and that, until a demand for such equipment exists, no single manufacturer is therefore likely to undertake its development. I can only reiterate the pious hope expressed in the Conclusion to the paper. All the signs point to the ultimate use of the direct-current system for the transport of electricity in bulk and over long distances. The immediate necessity that now arises is for the conducting of a large-scale experiment with a view to gathering further technical data and obtaining much-needed operating experience. Such an experiment can only be undertaken by the electrical industry as a whole.

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* H. Rissik: *Journal I.E.E.*, 1933, vol. 72, p. 440.

* See Bibliography, (3), on page 8.

RADIOLOGICAL AND ELECTRO-MEDICAL APPARATUS.*

By L. G. H. Sarsfield, M.Sc.(Eng.), Member.

INTRODUCTION.

In this review attention is drawn to progress in electrical matters associated with the following subjects: X-rays, diathermy, high-frequency currents, ultra-violet radiation, and miscellaneous electrical treatments.

The comparatively extensive treatment of the subject of apparatus for X-ray purposes has been necessary owing to the fact that so many important components are found in this type of equipment, and because considerable developments have marked recent radiological work not only in the medical but also in the industrial sphere. Radiology represents, perhaps, the most important activity connected with the application of electricity to medicine. Some outstanding X-ray developments mentioned are: means for preventing the emergence of unwanted X-radiation; the wide application of the shock-proof principle by using earthed sheathing for tubes, high-voltage generators, and cables; the production of high-power tubes and rectifying valves, including experimental models; the increased ease and accuracy of control methods and timing; and the improvement of associated equipment such as couches, tube stands, and photographic material.

In diathermy the introduction of continuous-wave valve oscillators has added a new surgical instrument of high power which is flexible and easy to control. On the treatment side of this subject the use of very high frequencies has permitted the production of artificial fever without the necessity for electrodes in contact with the patient.

The many new types of generators of ultra-violet light have encouraged the use of this type of radiation in connection with physical investigations and in medical work. Some experiments on this subject are referred to in this review, and mention is made of a new cadmium lamp having interesting features.

Safety and portability characterize the newest apparatus designed to provide direct, alternating, and interrupted currents for medical purposes. As the review shows, many modern sets combine all these services in one comprehensive instrument.

X-RAYS.

From the earliest days of radiology and the application of electricity to medicine British, American, and Continental products have been associated in the development of equipment. A number of recent innovations, especially in connection with radiological apparatus, have originated abroad, but they have quickly influenced technique in this country. Considerable reference will therefore be made to them in this review.

X-Ray Tubes.

While it is probable that a few gas tubes are still to be found in hospitals and experimental establishments, the great majority of X-ray tubes now in use are of the vacuum type in which the cathode is a tungsten filament of spiral or helical form.

During the past three years there have been important developments in this vital piece of apparatus. The general tendency has been to provide X-ray protection in some form or other in new designs, particularly in tubes of the 100-kV(P)† class. The manufacture of protected tubes introduced about eight years ago on the Continent has within the last few years been taken up by most tube makers. The protection has taken the form of a lead band round that portion of the tube where the X-rays are generated, so as to prevent the emergence of rays except through the properly provided window. Additional X-ray protection is afforded along the length of the tube by the electrodes themselves, and also by sleeves of lead-loaded insulating material extending from the centre to the ends of the tube. In most instances the design of the cathode and of the anode is such as to absorb secondary radiation in an axial direction.

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* A review of progress.

† 100 kilovolts peak value.

The method of fitting the lead differs on various models. For instance, the Philips type has the protective band mounted on a chrome-iron alloy sleeve actually sealed to the glass envelope. In the Siemens type a metal sleeve is assembled external to the glass, thus avoiding a glass-to-metal seal. The lead protection is mounted on this metal sleeve, which is electrically connected to a chrome nickel-iron baffle surrounding the anode and the cathode in the discharge region, so as to avoid puncture of the glass by cathode bombardment.

The Andrews " Protexray " tube (British) also has an electron baffle, but this is not in contact with the external sleeve. In this tube the lead band is mounted outside the glass envelope, and the danger of puncture of the glass at this point by electron bombardment is minimized by a metal shield inside the glass surrounding the electrodes and connected to the cathode.

In the Coolidge model the tube itself is cylindrical and the ray protection is a complete cylinder into which the tube may be easily slipped. Centrally the cylinder carries the main lead band, and on either side lead-loaded insulating compound. This tube has interchangeable anode-cooling arrangements for water and air, and it is interesting to note that in the discharge region no baffle has been necessary to protect the glass from puncture.

It is impossible here to go into the variety of sizes and ratings of tubes available to-day. The particulars already given apply to tubes of medium size for general radiography. These tubes are available from different makers in ratings varying from 2·5 to 20 kW, the power (an arbitrary value, the product of mean current and peak kilovolts permissible for 1 sec.) being dependent upon the area of the anode focus and upon the method of cooling. Some modern tubes are fitted with two filaments corresponding to fine and broad foci, and two power ratings are then allotted. A switch embodied in the cathode cap permits the choice of either filament. The water-cooled tubes of this class are thermo-syphon operated. The continuous rating for the stationary radiator-cooled anode is 560 watts, and at the rated voltage the common figure for current is 4 mA.

Owing to the possible generation of steam and to the risk of the liquid being upset, small water-cooled tubes have not the convenience of the radiator-cooled tubes. Messrs. Philips have therefore recently brought out a new radiator tube in sizes of from 2½ to 20 kW.

Messrs. C. Andrews have also produced a " Goliath " radiator-cooled model for ratings up to 10 kW. Although some plain X-ray tubes are still available, the principle of ray protection is applied in the manufacture of the majority of modern ranges up to 200 kV(P). Plain uncovered envelopes are used on extra-high-voltage tubes and also on tubes enclosed in tanks containing oil. In one high-voltage tube designed for 400 kV(P) the glass envelope is melon-shaped with axial cylindrical extensions, and partial protection is achieved by embedding the tungsten target and hooding the filament in copper. On the anode side an axial hole admits the electrons, while a hole at right angles to the first allows the X-ray beam to emerge. One of these tubes is in use at the Middlesex Hospital.

On this page is a typical table taken from a rating sheet of a modern 6-kW British tube (the Protexray). The figures are for working on rectified current.

	kV(P)	Milliamperes								
		Seconds								5 mins.
		1/10	1/5	1/2	1	2	5	10	20	
Radiator-cooled	112	85	75	65	60	54	43	33	20	4
Water-cooled (thermo-syphon)	112	106	93	81	75	67	54	41	25	5

The addition of ray-protecting fittings to X-ray tubes has been followed by the provision of electrical safety. Indeed, the question of electrical safety has received the major proportion of attention in the development of tubes during the past few years. The method adopted has been the envelopment of the tube in earthed metal. The success of this plan is of course dependent on the ability to take earthed-sheath leads to the tube and to unite the covering of these leads to that of the tube so as to form a continuous sheath right from the tube to the high-voltage generator. It used to be common to enclose an X-ray tube in a cumbersome lead box which served the dual purpose of X-ray protection and earth shielding. Now that the question of X-ray protection has been dealt with on the tube itself, the earth sheathing may be a light metal housing which can also be carried on the tube. This method of obtaining electrical safety has been used with the range of Metalix tubes now available in sizes up to 200 kV. This range was developed from the original Metalix " Junior," a small unit for about 45 kV. It is interesting to note, in passing, that one of these " Juniors " was used in the examination of Prof. Piccard's aluminium gondola constructed for his ascents to high altitudes. In the case of the 200-kV Metalix tube, arrangements are made whereby the space may be filled with compressed air. Water-cooling of the anode is employed.

The British model built on the same lines is the Andrews " Shock Free," which operates at 110 kV(P) and 4 mA continuously. This model is claimed to be the smallest of its type for its rating. The space between the tube and the earth sheath is filled with insulating oil which assists in reducing the dimensions to a minimum.

The sheath employed in German (Siemens) tubes is heavier, consisting of lead-loaded porcelain externally metallized. This sheathing is cylindrical, in conformity with the shape of the enclosed tube, and does not seriously increase the size of the assembly. The porcelain helps internal insulation, and oil is used for cooling.

The scheme adopted in a new French (Pilon) design is the immersion of the tube in oil in an earthed vessel. A special small tube, permissible by the presence of oil, makes the arrangement a compact one.

The Victor Corporation of America have extended the plan introduced some years ago for their dental outfit, whereby a transformer and tube are enclosed in a tank of oil called the tube head. A 90-kV(P) apparatus of this type for general radiography has been available for three years. In each case a special small tube is designed to be used with the set. The fact that the high-voltage unit is completely immersed in oil allows it to be small enough not to be unwieldy when properly supported and counter-weighted, and the enclosure in earthed metal provides safety from electrical shock and freedom from any external electrical field. The year 1933 saw the employment of this principle for 300-kV(P) apparatus for the investigation of welds on the Hoover Dam penstocks.

A special range of metal-clad tubes on the lines of the Metalix "Junior" has been marketed by Messrs. Philips for research purposes. These tubes have been adapted to the requirements of crystal analysis and may be fitted with anodes of various metals, depending on the character of the radiation desired.

The conversion of an ordinary X-ray tube to a shockproof one may be effected by enclosing it in an earthed case. A convenient case has been developed by W. E. Schall for this purpose. It is arranged to house tubes of the 110-kV class and is of compact form, adding comparatively little weight to the tube. An interesting point in the design is the provision at the centre of the case of a condenser bushing which withstands the potential difference between the case and the tube. Other firms also manufacture similar fittings.

Some interesting tubes have been constructed for special experimental work. A high-power tube, described by V. E. Pullin, Director of Radiological Research, and C. Croxson in the *Journal of Scientific Instruments* (1931, vol. 8, p. 273), was designed and constructed in the Research Department, Woolwich. It has been operated for extended periods at 390 kV(P) and 20 mA. This tube has a melon-shaped glass bulb with axial extensions. During use it is continuously evacuated and is mounted on a stand with its pumping system. The water-cooled target is a gold disc, set in a copper hood. The main beam of X-rays traverses part of the copper hood. The cathode is a tungsten filament enclosed in a nickel-plated copper tube. The electrode sealing-joints and the exhaust pipe can be broken down and remade readily, so that the tube can be dismantled for repairs and reassembled with little trouble. Penetration of 5½ in. of steel has been achieved with this unit.

Continuously-evacuated X-ray tubes and rectifiers are now being manufactured by the Metropolitan-Vickers Co.

A. Müller has described a high-current tube with a rotating anode which was developed by him at the Royal Institution and at the General Electric Co.'s Research Laboratories. Müller's tube will run steadily at 50 000–60 000 volts and 100 mA, and is designed with a view to the application of high-power X-rays to crystal analysis. Special features of the tube are a combination of water-cooling with anode rotation, and the use of the vacuum-type stuffing box through which the rotating shaft passes. The rotating-anode principle for large-power dissipation has been used experimentally since the early days of radiography.

A Philips tube incorporating a rotating anode has been available commercially since 1931. In this model, called the "Rotalix," the rotation of the anode is obtained by induction from a special winding incorporated in the body of the tube.

In the realm of very high-voltage radiography an achievement of interest was the production in 1932 by W. D. Coolidge of a 900-kV(P) cascade type of tube. This tube has been in operation in the Memorial Hospital, New York, for the purpose of comparison of X-rays with γ rays of radium.

Another interesting research tube built in 1932–3 by Crane and Lauritson, at the California Institute of Technology, incorporates a standard 220-kV (r.m.s.) transformer bushing of porcelain as the insulating envelope. This supports an anode at one end, while at the other end is mounted a cylindrical tank in which the cathode is fitted. The tube has worked at 650 kV(P) and is continuously evacuated.

Still another special tube is one made of Pyrex glass which has been run at 1½ million volts and was supplied from a Tesla coil. This apparatus has been in operation at the Carnegie Institute, Washington.

Earthed-Sheath Flexible Cables.

Although earthed-sheath high-voltage flexible cables have been employed in isolated instances on X-ray apparatus for a number of years, they have been developed considerably of late for use with earthed-sheath X-ray tubes.

The requirements of an X-ray cable are that it shall be as small and flexible as possible, that it shall have twin cores for filament heating, and that its sheath can be earthed. Where the cable is required to carry within its core the anode-cooling liquid, twin tubes are provided for this purpose.

From considerations of flexibility, rubber insulation at once recommended itself. It has been thought that minimum dimensions would be possible with oil-filled cable, but the success with rubber has already ensured its use up to now for all practical applications. Rubber cables have been employed for voltages up to 110 kV(P) between core and sheath, permitting 220 kV(P) across the X-ray tube.

Cables for this voltage are a little over 2 in. in diameter. Tests in the Research Department, Woolwich, have shown that it is possible to operate cables of this size for long periods with a potential difference of 200 kV(P) between the core and sheath. The minimum permissible diameter of rubber cable for a given voltage is not yet known, and cable makers are endeavouring to improve their product with a view to lightness, small dimensions, and flexibility. The reduction of the distance between the core and sheath naturally increases the capacitance of the cable, and this is not always advantageous.

The making-off of cable ends has called for ingenuity and care, especially in view of the need for keeping dimensions small. When cables are introduced into the earthed sheath of an X-ray tube the arrangement depends on the insulation utilized between this earthed sheath and the insulating envelope of the tube. The presence of compressed gas or of oil, as in the case of the Protex ray tube, may simplify the cable-end problem, especially in connection with surface leakage.

It is often necessary for earthed-sheath cables to terminate in free air, as, for instance, when they are connected to terminals at the high-voltage generator behind an earthed shield, or when they extend for use at the tube an existing bare-conductor system leading from a high-voltage generator. Manufacturers have evolved some satisfactory designs for this purpose. In general the plan adopted has been to take back the cable sheath from the live terminal and to increase the sheath diameter at its end in order to decrease the field intensity there. The termination of the sheath has therefore taken a conical form, and in some instances the cone end has been radiused in order to reduce the field intensity. Corona and surface sparking have thus been eliminated within the working range.

The hollow space between the cone and the cable insulation may be filled up with insulating material. Some manufacturers have employed porcelain for this purpose, threading it over the cable insulation and retaining it in position with some suitable mechanical device. Other manufacturers have adopted the plan of embedding the sheath end in a baffle comprising tape and solid insulation, so as to localize corona.

Where earthed-sheath cables of any considerable length have been employed, e.g. in the X-ray mobile laboratory mentioned later, it has been found necessary to take particular care in earthing the sheath. The high-frequency disturbances which are present, more or less, in all high-voltage generators for X-ray purposes tend to induce high-frequency potentials on the sheath, which therefore requires to be solidly earthed at both ends and, in some instances, at intervals between the ends.

Couches and Tube Stands.

The design of couches and tube stands has improved. The mechanical problems in X-ray engineering are numerous, and devices utilizing the counterbalancing principle for effortless movement have been developed to a high degree of perfection. The motor-driven couch has made its appearance. This unit is so arranged that it can be tilted to any desired position, from the vertical to the horizontal and beyond, so that an infirm patient may rest against it and be moved to any position without exertion. Hydraulic means have been introduced for regulating the vertical position of a patient during examination.

Welded structures have recently been adopted by a British firm for couches and tube stands. A design for a light welded couch comprising three panels has been carried out in sheet metal and light angle iron. The panels are hinged and permit a patient to be supported in a number of useful positions.

High-Voltage Generators and Rectifiers.

Except in cases of obsolete plant and experimental apparatus, the high-voltage unit comprises a step-up transformer, a high-voltage rectifier, and possibly a system of condensers. A great deal of radiography is done at voltages within the 100-kV(P) range, and for this work single-valve rectification (employing alternate half-waves of correct polarity) is frequently adopted. Four-valve full-wave rectification, though better from the point of view of transformer regulation and power output, is generally an expensive proposition on account of the cost of the valves, especially as with this arrangement each valve has to sustain the tube voltage. An American (Victor) set specially designed for high current-output is capable of operation at 1 000 mA and 85 kV(P). Constant-potential equipment (generally with a voltage-doubling circuit consisting of valves and condensers), which has been brought to the front within the last few years, has lost some of its popularity, even for high-voltage deep-therapy work. This may be because of the tendency for constant potential to be hard on tubes. An alternative means of obtaining high voltage with comparatively small transformers is offered by the Villard circuit, which secures the advantage of voltage-doubling and provides unidirectional pulses at half the transformer frequency. This type of high-voltage supply seems to be very suitable for X-ray tubes and is being freely adopted in modern apparatus.

While mechanical rectifiers are still obtainable commercially in this country, and are preferred in some radiological establishments, valve tubes have been very extensively taken up. They lend themselves to multiplying circuits, and have the advantages of silence and of absence of moving parts and spark discharge. In America, however, mechanical units of the disc and cross-arm type are still being marketed to a large extent, although, even there, valve tubes are gaining ground.

There has been steady development in the manufacture of vacuum-type hot-cathode valves. In this country, valves are manufactured for inverse voltages up to 220 kV(P) and capable of passing 100 mA continuously. Valves for twice this voltage are in use on the Continent.

Oil-immersed valves are being used in America. The enclosing tanks are earthed and form part of a shock-proof installation.

An interesting innovation is the development on the Continent of a valve and X-ray tube in one envelope. This combined tube and rectifier is adapted for medium-voltage work and effects an important saving of space.

The Metalix type of valve, in which the anode forms part of a metal end-cap enclosing the cathode, is being used a good deal in this country. The large anode cap permits good heat radiation, a reduction of the space charge, and therefore better filament emission and high current capacity with small voltage-drop. The anode cap also forms a screen to obscure the light of the filament. The latest Philips valve, however, operates with a gas discharge and has a dull-emitter filament. The valve comprises a number of cells in series, the filament in a cell at one end providing the emission for the complete valve. Condensers connected across the cells control the voltage distribution down its length. The current capacity of the valve is 1 000 mA, with a drop of 40 volts, and the filament absorbs only 7 watts.

Another type of generator in which valves and condensers are employed is that arranged for high discharge currents of short duration without withdrawing heavy current from the mains. The condensers are charged during a comparatively long period, say 10 secs., to a predetermined voltage, at which it is desired to operate the tube, and then by suitable change-over switches the condensers are made to discharge through the tube. This is one method for getting over the very real problem, from the mains point of view, of passing instantaneous heavy currents through X-ray tubes. Another is the use of a 3-phase supply and an X-ray transformer with appropriate rectification—generally a 6-valve system. The latter alternative was recently adopted where a supply undertaking refused to permit certain heavy loads to be applied on a particular installation on the system.

At the Congress of the British Institute of Radiology in December, 1933, Dr. A. Bouwers demonstrated a complete X-ray apparatus of novel form in which the core of the transformer is arranged round the tube and the windings are assembled in an annular space cut in the iron. The tube has a cylindrical wall which is practically all metal and may be earthed. The rays emerge from a fine focus through a hole in the core. The whole apparatus weighs only 10 lb.

Transformers and Control Gear.

In very high-voltage work impulse generators and Tesla coils are being employed.

X-ray transformers are being manufactured on now familiar lines, and if there is any perceptible change it is in their general quality and serviceableness, owing to a better knowledge of materials and of the conditions to be met. The reliability of modern X-ray transformers is of a high order, and this can be said, not only of medical equipments, but also of apparatus adapted to radiology in engineering where their duty more nearly approaches the continuous conditions required in power engineering.

Porcelain, glass, ebonite, and varnished paper, are employed in the construction of terminal bushings of different types. Condenser and oil-filled designs are also sometimes seen.

Open-core air-insulated filament-heating transformers are used, but the more general practice, especially in England, is to adopt the oil-immersed closed-core arrangement.

Voltage control of an X-ray transformer is generally effected by supplying the primary from a tapped auto-transformer. Incorporated in most modern arrangements of this sort are additional tappings to compensate for line-voltage variations.

A method used by some Continental firms, and at least by one British one, for voltage control of X-ray transformers is by tappings on the high-voltage winding. This makes for greater efficiency, since no auto-transformer is required, the X-ray transformer core is always operating at full density, and the secondary resistance is not constant for all voltages as when the whole winding is employed, but is proportional to the number of turns in use. In the British design the current is taken from the tappings by small contactors which are oil-immersed with the transformer and are worked from direct current, through a copper-oxide rectifier, at a low voltage. The contacts are mounted on light insulating rods carried on the armatures, which are moved by coils about the size of bell bobbins.

Many excellent instruments have been introduced for exposure timing. The simplest of these are clockwork mechanisms designed to close and open contacts in circuit with a contactor operating the X-ray transformer primary. Other devices include the Gaiffe milliampere-second relay. Yet another which merits mention is the Philips timer, which incorporates a valve the grid of which is supplied through a variable resistance. A condenser charging-current passing through this resistance reduces the negative potential of the grid, which is normally maintained at a value sufficient to prevent the flow of anode current. The anode circuit controls the X-ray transformer primary through a contactor, and the time taken by the grid to reach a potential which will permit anode current to flow is governed by the condenser current, which in turn is governed by the resistance. This can be set so as to correspond to the time interval required. The instrument gives accurate timing within single-cycle limits on a range from $\frac{1}{10}$ sec. to 8 secs. A British instrument conceived on similar lines is now on the market.

Timing is also effected by a shutter similar to that of a camera and fitted on the X-ray tube window. An electrical device combining such a shutter with a stop-watch has been developed for experimental work in the National Physical Laboratory. The lead shutter is solenoid-operated and is connected with the watch mechanism so that time can be accurately measured.

The Hammer docimeter has been developed during the past three or four years. It employs the X-rays themselves to control the exposure and is well adapted to medical work. The rays impinge on a cell containing an electrode which, under the ionization effect of the rays, acquires a charge. When this charge reaches a predetermined value, contacts are closed by a leaf electrometer and a unit of radiation is recorded on a counting mechanism. This unit can be compared with a radium standard.

Experimental work done at the National Physical Laboratory on the realization of the röntgen has demonstrated the accurate agreement of German and American results with British ones.

The use of X-rays for the study of pearls has been in progress for some time. Experiments made in the National Physical Laboratory with a constant-potential equipment, arranged by Messrs. Watson and Son, have demonstrated the superior possibilities of spectrum examination over ordinary radiography.

The question of electrical safety has been dealt with by the enclosure of high-voltage apparatus in various types of earthed containers. Shock-proof apparatus is available for small and large powers. Shock-proof apparatus was commended by the International Committee in Paris in 1931. Within the last two or three years Continental and American authorities have issued detailed regulations governing electrical and X-ray safety.

The chief instruments used in connection with practical

X-ray work are the milliammeter for measuring the tube current and the voltmeter for measuring the transformer secondary or tube voltage, the latter measurement being made either by an instrument connected on the primary side and calibrated according to transformer ratio, or by an instrument connected on the secondary side. The tube current can, on some circuits, be measured at earth potential and, where this is done, the milliammeter can be mounted conveniently on the control panel. The modern tendency is to utilize current-measuring instruments on the control panel if possible. A number of good designs of milliammeters are, however, available for connecting in high-voltage circuits. Ballistic milliammeters have also been introduced. A development last year by Messrs. Everett, Edgcumbe of glass which cannot hold a charge has banished the irregularities of instrument readings due to static and high-frequency electrification of the glass.

Voltage measurement is always difficult with X-ray work. The alternative spark-gap often mounted with the apparatus is gradually disappearing, and calibrations giving the tube voltage for various loads and control settings are used instead. It is necessary to know the wave-form in order to get an accurate measurement of the voltage. Wave-forms are often very irregular, especially with mechanical rectification. A Duddell type of oscillograph has been adapted with special insulating mountings for this work in the Research Department, Woolwich. Constant-potential equipments lend themselves to convenient measurement of voltage, since it is comparatively simple to ascertain the value of the maximum voltage and the difference between the maximum and minimum voltages is generally known. Among the methods for ascertaining the maximum value is the use of a tapping from a potential divider to energize a low-voltage electrostatic instrument. The charging current of a known condenser connected to the high-voltage circuit has also been employed for tube-voltage measurement. The rotating voltmeter has been proposed for X-ray work. A number of articles describing various arrangements for experimental purposes have also appeared in journals dealing with physics.

Control panels, whether of the wall or desk type, or mounted on movable pillars, are becoming more compact and simple to operate. Dwarf instruments are being very freely employed. An attractive British control unit of recent development has the instrument dials set below the surface of the panel and provided with ports so that they are illuminated by a concealed lamp. This design facilitates screening in a darkened room, the light being sufficient to illuminate the instruments but not to dazzle the operator for his visual observations.

The control of X-ray transformer primary voltage by an induction regulator has been adopted by some British manufacturers.

There are two important cases of the development of specific X-ray plant for engineering applications. One is the mobile X-ray laboratory designed and constructed in the Research Department, Woolwich. This equipment, which incorporates a 250-kV(P) generator, with remote control, long high-voltage earthed-sheath flexible cables, X-ray tube and accessories, dark room, and photographic supplies, is assembled on a motor lorry, the engine of which supplies all the electric power required. The cables permit the tube to be used at a distance of 30 yards from the lorry and provide a safe and robust transmission. They can trail the ground or be taken through windows, so that X-rays can be used in locations where the safety or flexibility of the equipment is vital. The other equipment now in use on boiler-welding work is a Philips product and comprises a complete high-voltage unit in a rectangular earthed case, and a shock-proof X-ray tube is connected thereto by cables having an earthed sheath. This apparatus, together with neat controls, is assembled on a pneumatic-tyred wheel base which can conveniently be attached to a motor-car for transport, and the whole can easily be lifted by a crane in an engineering shop.

X-ray Photographic Supplies.

Photographic apparatus has made important advances. British and foreign manufacturers have been experimenting with the introduction into X-ray photographic emulsions of metallic salts in order to increase the speed of the film.

Intensifying screens are of greatly improved quality.

New intensifying screens have been developed in this country by L. Levy and D. W. West. These screens employ "flourazure" (zinc sulphide) and have two important advantages—less opacity and greater actinic activity to X-radiation. These screens are reported to have given an increase in speed of the order of from 3 : 1 to 10 : 1, depending on the voltage, the depth of penetration, etc. The results of researches on the elimination of after-glow from these screens have recently been published.

Zinc-sulphide fluorescent screens are now available commercially.

The Sinegran is an example of a Continental screen which is giving a higher intensification factor and sharper contrast than was obtainable with the screens of a year or two ago. Similar improvements affording greater speed and better contrast have characterized the latest films, which are exemplified by the Ilford (British) and Gaevert (Continental) products.

The reduction of exposure time as a result of recent photographic progress has already been of great importance in medical work for moving subjects and in metallography for the X-ray penetration of thick specimens.

GRENZ RAYS.

Apparatus for Grenz rays has been marketed by Continental firms. These rays, used in dermatology and of comparatively long wavelength, are generated in a tube employing from 10 to 15 kV(P) and 10 to 15 mA, and have a wavelength between those of X-rays and ultra-violet light.

DIATHERMY.

Diathermy is now applied to a wide range of diseases, including internal secretions, rheumatic disorders, deafness, skin troubles, and nervous ailments. The increased use has given an impetus to the improvement of apparatus in many ways. The efficiency, compactness, and finish, of many designs are definitely better. In the sphere of diathermic treatment, novel electrodes have been introduced. A plastic electrode has been applied to the use of diathermy on irregular surfaces of the body.

Perhaps more striking advances in diathermy have been made on the surgical side. This applies in apparatus employing the spark oscillator system as well as in the more recent valve oscillator. It used to be said that improved control and adjustment was required; this desideratum has been realized in many British machines. Attention has been given to the control of coupling arrangements of condensers and inductances, and also to spark-gap adjustment, so that current, voltage, and frequency, are better regulated.

An example of the spark-gap type of apparatus is afforded by a machine due to Messrs. Newton and Wright. The quenched-spark circuit employs gaps only 1/3000 in. long, and any wear during working may be taken up by a simple adjusting device. Circuit control permits a variety of cutting and coagulating currents. Conditions can be adjusted to such a nicety that interior bladder operations may be done, and the absence of bleeding facilitates optical inspection with the aid of a lamp and telescope.

The valve oscillator system is exemplified in the Chirotherm, the new instrument developed by Messrs. Watson and Son. An Osram valve is employed. It is claimed that this machine can handle high powers, is electrically flexible, and operates silently, whilst regular pulses of current (continuous wave) contribute to easy and efficient cutting. This machine has been very successfully applied to the hitherto difficult operation of fat cutting, and the clean, rapid strokes through ordinary flesh permit ready healing. The machine, which is available as a portable or fixed unit, offers simple manipulation for circuit control, valve-filament regulation, and intensity adjustment.

High-frequency currents are also being applied by a method in which the part of the patient requiring treatment is placed between the plates of an air condenser. The plates are insulated and connected to a generator which produces a potential difference of about 1 000 volts at a frequency of from 10 to 20 million cycles per sec. The patient is introduced into the field between the plates, and artificial fever is produced. The sensation is one of pleasant uniform heating. Apparatus of this type has been tried out in France and America, and now a very successful model with an Osram valve oscillator has been produced in this country by Messrs. Watson and Son. The instrument is in two sizes for local and general application. In the latter the machine-cabinet top forms a couch. The circuit is similar to that of the Chirotherm and employs alternating current from the mains, which is rectified by a mercury-vapour tube. An important point in the operation of this unit is the cooling of the valve; for this purpose a fan is incorporated. Ultra-short wavelengths corresponding to from 20 to 40 million cycles per sec. have been tried, but selective heating becomes very pronounced, and medical conclusions on this type of apparatus are premature.

HIGH-FREQUENCY CURRENTS.

Another form of high-frequency current which has become increasingly popular is the so-called violet ray. In this the currents, much smaller than are generally used in diathermy, are passed to the patient in high-voltage damped waves at 100 000 cycles per sec. from an induction coil or Tesla coil through a vacuum electrode, which glows a violet colour, and is accompanied by pale sparks. Modern sets run on a.c. or d.c. mains, a hammer interruptor being employed. In small sets the Tesla coil is often fitted inside the handle carrying the vacuum electrode.

ULTRA-VIOLET RAYS.

The electric spark produced by an electrostatic machine, spark coil, or transformer, is still used experimentally in the investigation of ultra-violet light. Carbon and tungsten arc-lamps are, however, more popular. In contrast with spark apparatus, arc lamps work on low-voltage supplies but carry heavy currents. In open air, carbon (plain or impregnated) and metallic electrodes are used. Flame carbons, made by impregnating or coring ordinary carbons, are richer in ultra-violet light than ordinary carbons, and give a wealth of intense lines down to 200 $\mu\mu$. They require a current of from 25 to 75 amperes. Metal arcs (iron, copper, tungsten) give good radiation at 5 to 15 amperes, but will not run on alternating current. They take direct current at from 100 to 150 volts. When cheap metals are employed the arc represents an economical source of ultra-violet radiation.

The mercury-vapour quartz lamp is the most powerful and efficient source of ultra-violet radiation at present available, its spectrum being limited by the quartz. The electrodes are supported in the quartz tube. The lamp can be worked from a.c. or d.c. mains provided that suitable control is chosen.

High-power incandescent lamps (300–500 watts) in special glass envelopes have been used for domestic radiation, and it is claimed that useful amounts of ultra-violet light are obtained by this means.

Infra-red rays from banks of carbon lamps, and radiation from bowl fires, are being utilized increasingly for the relief of rheumatic and similar ailments. Various simple mechanical arrangements are being developed for holding and boxing-in the heating source and for applying the treatment to different parts of the body.

The standard form of quartz tube employed to-day is the horizontal type, which must be tilted to start the arc. A variety of forms of vacuum-type arc are being manufactured in this country. Two leading firms are the Hewittic Electric Co. and the Hanovia Quartz Lamp Co. One of the chief recent developments, however, is the production by Messrs. Kelvin, Bottomley, and Baird, of an atmospheric type of tube which is air-cooled and self-starting. A water-cooled model is available and this permits a close approach of the tube to the object being radiated. Quartz lenses are now used for concentrating the beam. The useful life of the modern evacuated quartz lamp is about 1 000 hours, by which time the efficiency has dropped to about 50 per cent owing to devitrification of the quartz, the deposits thereon, and failure of the vacuum.

In four communications during 1932 to the *British Journal of Radiology*, E. A. Owen and P. Wright have published accounts of work on the intensity and quality of ultra-violet radiation from the Sheidt tube and various arcs, including carbon (cored and plain), tungsten, iron, and graphite. These accounts give information as to the physical characteristics of the Sheidt tube, a cold operating unit with comparatively small total ultra-violet radiation but with rich output in the region of 260 $\mu\mu$, and also as to spectra of different parts of various arcs and the dependence of radiation on arc length.

A cadmium lamp has recently been placed on the market by a German firm. It is claimed that cadmium light combines the spectral properties and effects of the mercury quartz-lamp and the carbon arc-lamp, and is rich in ultra-violet rays.

ELECTRICITY FOR TREATMENT AND MISCELLANEOUS MEDICAL PURPOSES

Under the names of galvanic, sinusoidal, and faradic currents, electrical energy is applied to the human body for a variety of medical purposes. The galvanic current is direct, the sinusoidal is alternating, while the faradic is that obtained from the secondary of a coil the primary of which carries interrupted current. An interesting application of galvanism is for the deposition of chemical salts (e.g. zinc) on sensitive parts, such as nasal passages.

Although a general improvement of dry cells has made small portable apparatus for providing galvanic and faradic currents more satisfactory, there is an increasing tendency to work this type of equipment from the mains. Many sets are fitted with cells for independent operation, but also have plug-and-socket connections and appropriate resistances, so that they can be used on direct current if desired. In faradic apparatus the current to the patient is varied by coil or core adjustment, so as to alter the coupling. In high-power sets secondary cells are sometimes used.

For sinusoidal current double-wound transformers are now being freely used. Inverted rotary convertors or small motor-generators are required when direct-current supply alone is available. This scheme permits of there being no earth connection in the electricity supply to the patient, and so the danger of shock due to accidental earthing of the patient is reduced. Circuits of this type were recommended in a Ministry of Health Memorandum published in 1932. Voltages up to 60 are common for sinusoidal treatment.

Electric current is also used for the heating of cauterizing instruments (up to 50 watts at low voltage) and for local illumination. The increasing application of electricity in the medical sphere (even medical electroplating is now being used) and the consequent facilities for experimental work with various kinds of current have led to the combination in one comprehensive machine for operation on a.c. mains of circuits which will deliver every form of current required. In connection with cautery or diathermic surgery, lighting of the region of the operation is sometimes of great importance, so that it is very convenient to have a lighting circuit available with a treatment apparatus.

Some excellent examples are available from British manufacturers. A typical machine may well comprise a transformer with two or three secondary windings and a variety of voltages for sinusoidal current, cautery, and local illumination, while, in addition, a little motor-generator is provided to supply direct current for galvanic and faradic currents. The generator has a double-wound armature, so as to provide a circuit without an earth connection for use on the patient. Regulating resistances for use in the patient's circuit complete the control arrangements. A new diathermy unit recently examined by the author incorporated apparatus for several electrical treatments in the same pedestal. The development of oxide-film rectifiers has permitted units of this type to be substituted for rotary ones for obtaining galvanic and faradic currents from an alternating source. The Solustat is an example of a new comprehensive apparatus constructed on these lines.

Thermo-electric thermometers are being introduced for determining internal temperatures.

Magnets are still being employed with success for the extraction of metallic particles from the eye.

The electro-cardiograph remains an instrument of great value, and experimental work is progressing on the use of low voltages in this sphere.

THE EQUIPMENT AND OPERATION OF A MODERN METER AND TEST DEPARTMENT.

By JOHN B. LEES, Associate Member.

(*Paper received* 15*th August*, 1933; *and read before the* METER AND INSTRUMENT SECTION 5*th January*, 1934.)

SUMMARY.

The increasing interest in their meter departments which is being shown by the managements of electricity supply undertakings is a matter for congratulation and is resulting in a very encouraging improvement in meter-engineering practice.

In this paper testing-equipment design is discussed and the conclusion is drawn that primary resistance-regulated current-loading transformers can be satisfactorily employed. Good electrical performance is considered to be the most important feature of a single-phase meter; and a new method of testing to certify this feature is outlined. The merit of calibrating to special limits of error is discussed, together with routine methods of testing single-phase and polyphase meters.

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(1) Introduction.
(2) Testing-Equipment Design.
(3) Considerations Affecting the Design of Testing Equipment.
(4) Special Single-Phase Meter Tests.
(5) Single-Phase Meter Testing.
(6) Three-Phase Meter Testing.

(1) INTRODUCTION.

The paper deals in a practical manner with certain considerations affecting the operation of a supply authority's meter department. The undertaking with which the author is connected has 46 000 meters on circuit, and at the present time the meter department is dealing with 10 000 meters per annum.

The section referring to test equipment stresses the ease with which test conditions can be produced, and points out that this matter cannot be given too much prominence. The manipulation of equipment providing test conditions, whilst important of itself, is only a secondary function in test work. The effect of the test conditions on the apparatus under test is the information sought for, from which it follows that any particular test conditions should be readily obtainable.

Experience shows that a very flexible equipment is essential. The modern tendency is towards making the meter department the electrical testing section, responsible for tests on a wide variety of apparatus. Most of the standard meter-testing equipments on the market are of very limited flexibility, being practically single-purpose equipments. In general, they are facsimiles of equipments used in meter manufacturers' test rooms. A flexible equipment cuts out duplication of apparatus and the use of much temporary wiring, which is difficult to trace, increases the risk of damage to apparatus, and creates a slipshod habit of mind.

In single-phase meter testing, speed is not divorced from accuracy if intensively-organized methods are used. It is in fact advisable to get through this work as rapidly as possible so as to leave the maximum of time for polyphase-meter and special testing, which is of necessity protracted. Quite apart from performance on circuit, a single-phase meter with a straight-line characteristic is valuable because such a characteristic makes it legitimate to test the meter at few points on the curve. It is, however, good practice to take selections at random from batches of, say, 50 meters and give these a full-curve test, because in some designs the curve compensation features are very critical and call for highly accurate assembly.

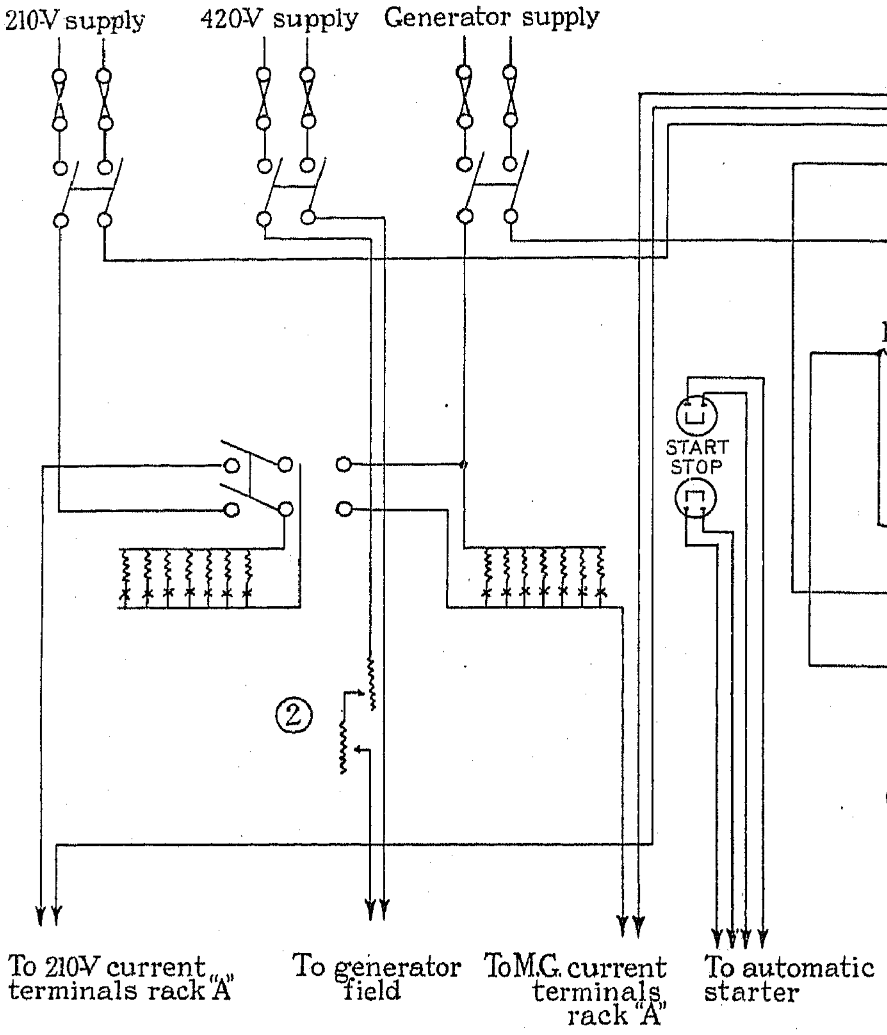
In the meter department of the undertaking with which the author is associated it is not the practice to test current and voltage transformers to ascertain their errors. Reliance is placed on manufacturers' figures with regard to voltage transformers. Current-transformer-operated meters are always calibrated with their transformers and then tested without. It is not difficult to calibrate a meter to a special curve, and it follows that a transformer-operated meter could be recovered from circuit (leaving the transformer *in situ*) and calibrated to its original 5-ampere test curve, just as easily as it could be calibrated to a curve deduced from transformer errors. It is not altogether satisfactory to rely on sub-standard instruments for measurements unless they are periodically checked.

(2) TESTING-EQUIPMENT DESIGN.

Direct-Current Equipment.

When the d.c. testing plant of the author's undertaking was laid down it was decided that a maximum loading of 100 amperes would be sufficient. This figure was determined largely by the fact that wherever possible it is the practice of the undertaking to give an a.c. supply for loads over 50 kW.

The d.c. equipment is divided into two sections, one having 210-volt supply and loading, the other being supplied from a motor-generator capable of giving a 70-volt 100-ampere output. The 210-volt loading is used when running prepayment meters out, on coin test, and for loads up to 20 amperes when testing apparatus at low-tension supply voltages. The motor-generator and resistance bank were originally installed in a cinema, which was changed over to alternating current; and the automatic starter used with it originally operated a cotton-mill hoist motor which was subsequently changed over to a.c. supply. Despite the fact that low-voltage loading obtained from a battery is the ideal, it was decided to use the available motor-generator and equipment, and to spend the money saved in this way on additional a.c. equipment, particularly as d.c. supply is rapidly being superseded by alternating current in the area concerned. The connections of the apparatus (see Fig. 1) enable the 210-volt loading to be thrown on to the motor-generator. This arrangement was necessary because the motor-generator bank could only be rearranged to give loads of 5 and 10 amperes and four stages of 20 amperes. Using generator-field regulation one can obtain and hold any load from 0·001 up to 100 amperes, with both 210-volt loading and the motor-generator resistance bank in use.



① *Links to put instrument on 210-V or M.G. loading.*
② *Generator-field rheostats.*

FIG. 1.

The sub-standard millivoltmeter consists of a "station" type case with a 0·1 per cent laboratory standard movement. The mirror scale is 12 in. long, has 150 divisions, and is reversed so as to bring the scale near to the front of the table. In conjunction with it a universal or series-type shunt is used which is made up of shunts rated at 1·5, 3·0, 7·5, 15, 30, 75, and 150 amperes. This system has no peer because the connections between the instrument and shunt are permanent, and no contact errors can arise.

Alternating-Current Equipment.

It was decided to install 3-phase a.c. equipment, for the following reasons. (*a*) It was considered that all polyphase apparatus should be tested polyphase, whether it could be tested single-phase or not. (*b*) Suitably designed 3-phase equipment can furnish conditions for three separate single-phase tests. (*c*) The equipment installed must be able to supply test conditions for protective gear, switch-tripping mechanisms, power-factor indicators, ammeters, voltmeters, and domestic apparatus.

The equipment (see Fig. 2) will supply any single-phase voltage from 5 to 500 volts, any line voltage from $5\sqrt{3}$ to $500\sqrt{3}$ volts with the voltage transformers connected delta/star, and any line voltage from 5 to 500 volts with the voltage transformers connected star/star. In addition, it will supply simultaneously three voltages which are not complementary, such as 110, 230, and 500 volts. It is arranged to supply any current from $\frac{1}{200}$ ampere up to 500 amperes single-phase or 3-phase, and any phase difference between current and voltage from zero lag to zero lead. Three separate single-phase tests at unity power factor and commercial voltages can be carried out, and three 230-volt single-phase tests at zero, unity, 0·5, and 0·866 power factors are possible by phase selection of either current or voltage.

The vector diagrams given in Fig. 3 illustrate how any three of these latter tests can be carried out simultaneously. The arrangement of the voltage circuits is given in Fig. 4, an inspection of which will show that the voltage-transformer primaries can be connected to

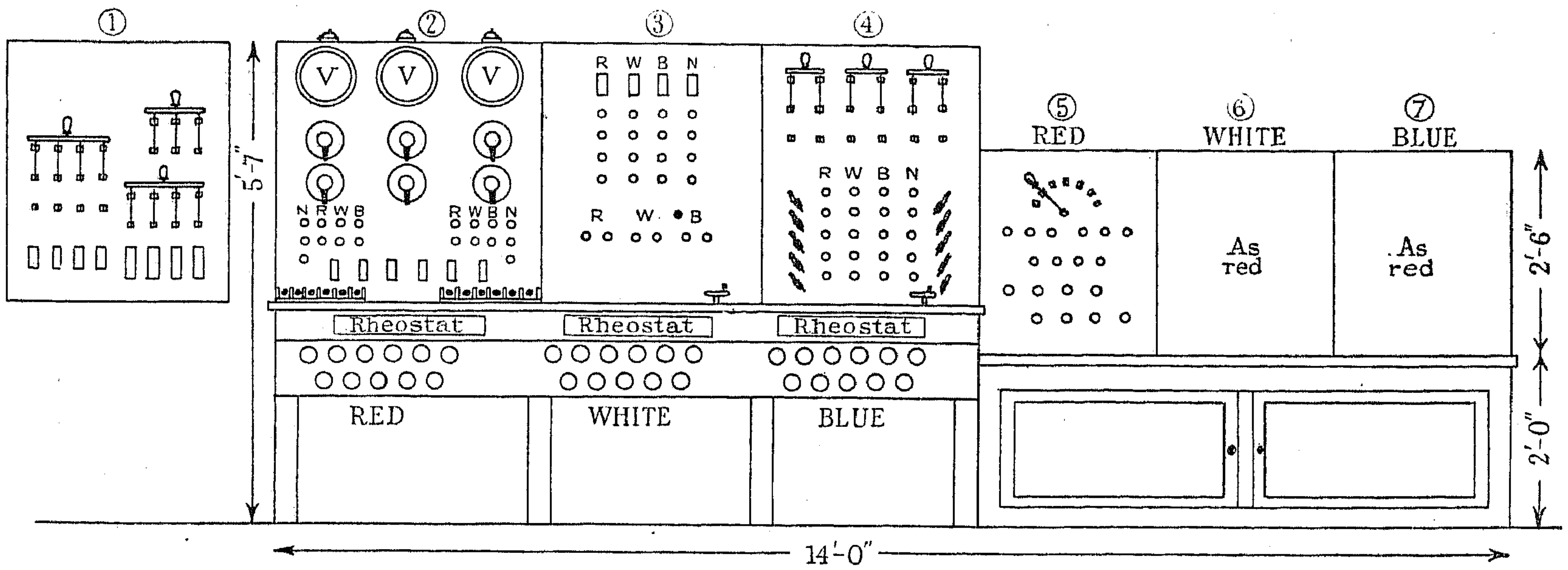


FIG. 2.—A.C. test equipment.

1. Control panel. 2. Voltage panel. 3. Instrument panel.
4. Current selection panel. 5, 6, and 7. Current loading panels.

the supply or the phase-shifter singly, in parallel, or to any pair of phases or any phase and neutral, and that the three can be connected either delta or star. It is also possible to connect the voltage-transformer secondaries to the test voltage circuits so as to give a variety of conditions. We can have a delta/delta, delta/star, star/delta, or star/star bank. It is quite common, for example, to have 230 volts on red phase and neutral, 400 volts on blue and white phases, and 100 volts on the photometer standard-lamp circuit. The phase-shifter is connected delta/star and has its rotor moved to such a position that when its indicator is at unity, and its star or output side is connected to a delta/star bank, the test voltages are in phase with the supply voltages having the same designation. In a delta/star-connected phase-shifter which has subtractive polarity and its rotor set to the natural unity power-factor position, the output voltages will lead input voltages by 30°. When this output is connected to a delta/star bank also having subtractive polarity the bank output pressures will lead input-to-shifter pressures by 60°. This explains the necessity for the setting of the shifter rotor. Phase-shifters are normally supplied set to give an output similar in phase relationship to the input at unity setting.

All the voltage and current test conditions are reproduced on the instrument panel; this avoids the undesirable use of temporary wiring, trailing about benches and floor. The arrangement of the current circuits (Fig. 5) enables each current loading panel to be connected to the supply in any way desired. Each set of regulation resistances can be used in series with either the 100-ampere or the 500-ampere current loading transformer primary. Each of the resistance banks has its ranges in the ratio 1/200, 1/40, 1/20, 1/10, 1/5, 1/4, 1/4, and 1/2. In addition, two 21in. variable rheostats are used for load-holding. The range of one is from 1/200 to 1/20 and that of the other from 1/10 to 1/5.

The transference of the current conditions is carried out in the following manner. First let us assume that we are dealing with a load not greater than 5 amperes. Two links are put in, joining A to B and C to D (Fig. 5), and the load is passed to the instrument-panel binding posts. When the load is in excess of 5 amperes the links are withdrawn, the primary of a precision current-transformer is connected to B and C, and the secondary of this transformer is connected to A and D. In the case of loads greater than 100 amperes the primary of the precision transformer is connected in series with the primary of the current transformer operating the apparatus under test, to the two studs E and F. The precision-transformer secondary is connected to A and D as before. It will be seen that no matter what the loading conditions are, either current or voltage, they are quickly and easily reproduced at the instrument panel.

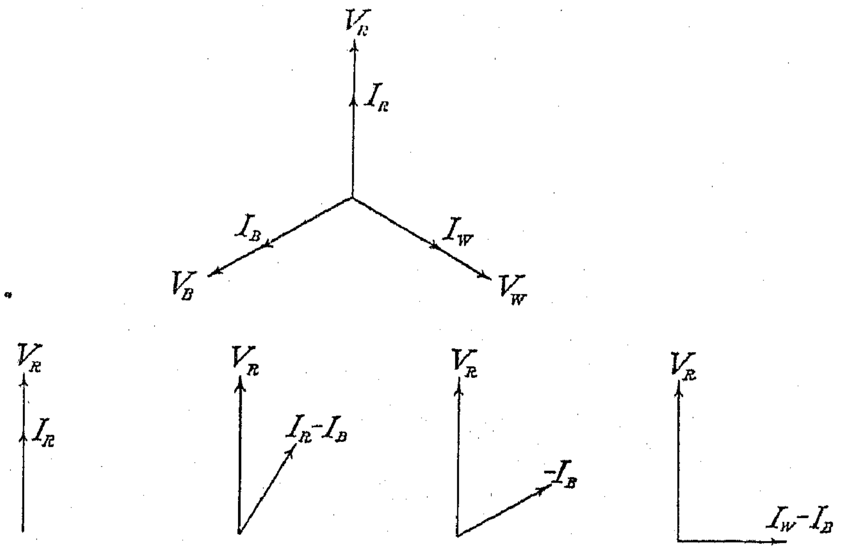


FIG. 3.

The two precision transformers each have self-contained ranges of 500, 250, 125, 100, 50, 20, and 10, to 5 amperes. Their capacity is 7·5 VA, their ratio error is 0·03 per cent from 125 per cent of full load to 5 per cent of full load on each range, and their phase-angle error is less than 1′ over the above load range. Their incorporation in the test equipment has reduced heavy-current measurement to the simplicity and accuracy which can be obtained on, say, 5-ampere tests.

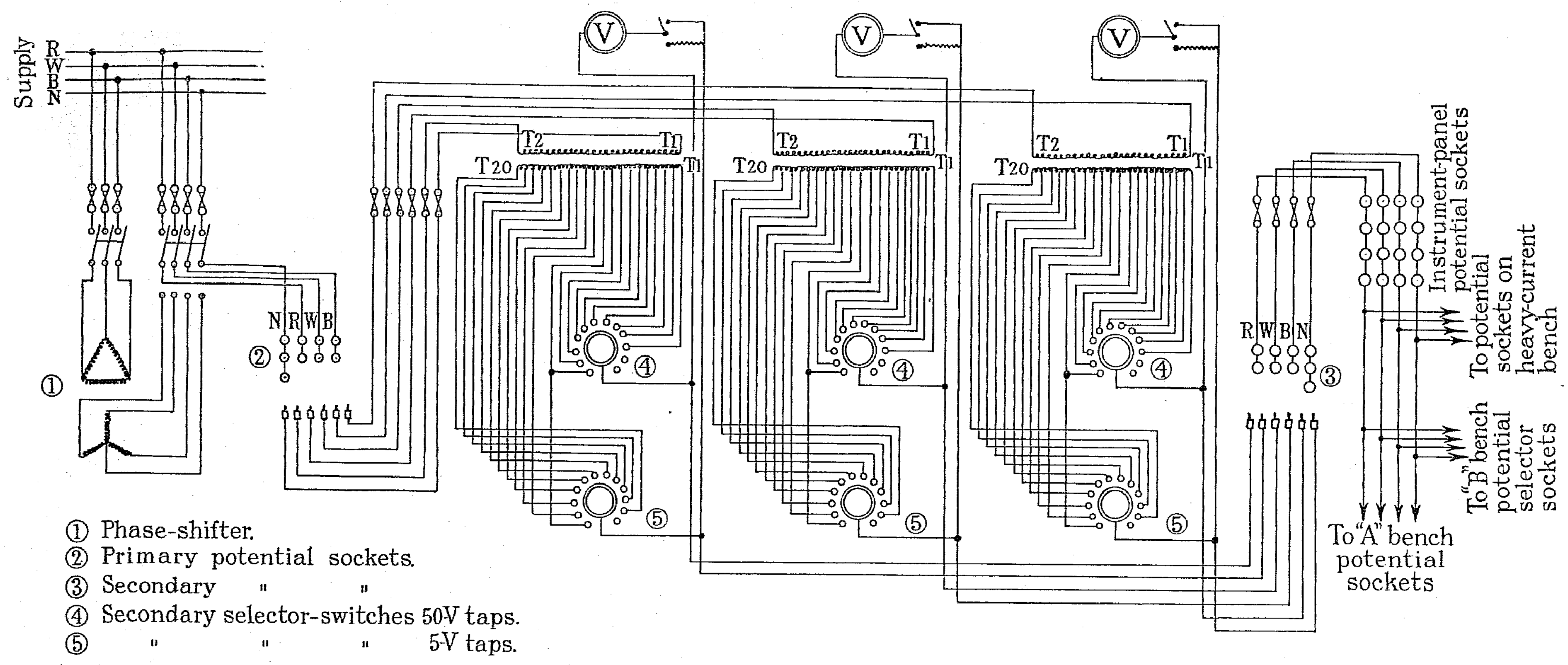
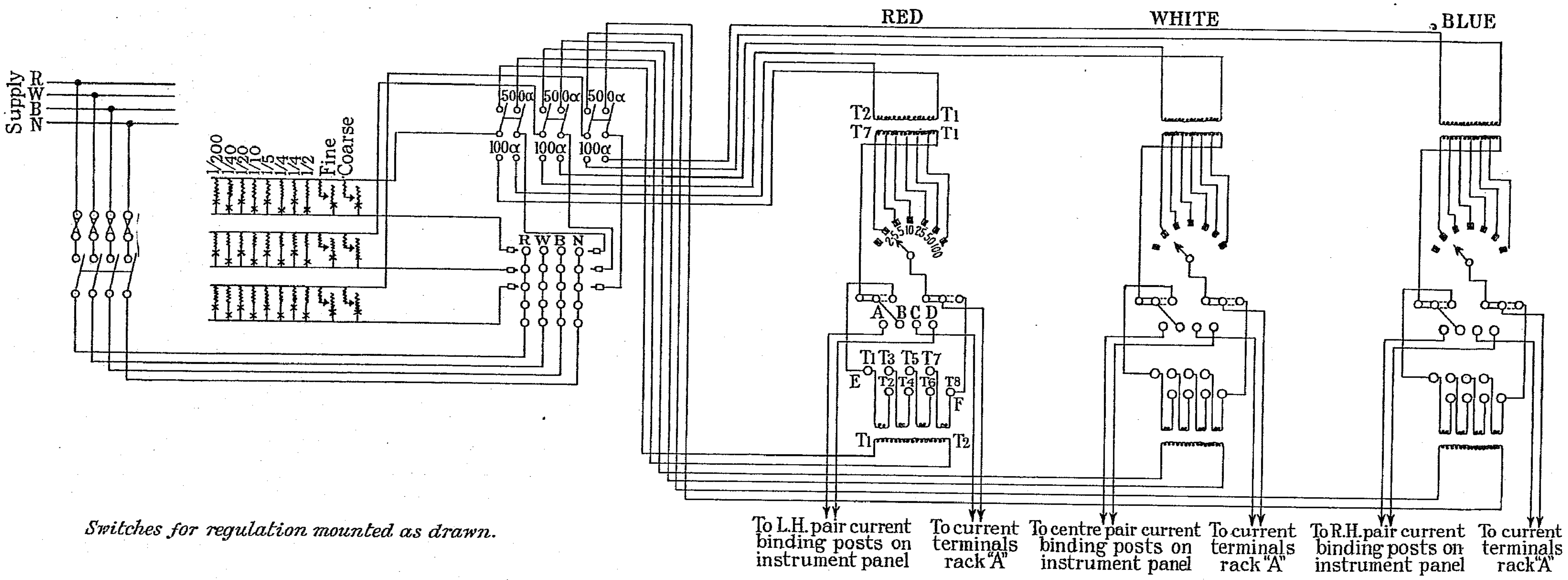

Supply
R
W
B
N
①
②
N R W B
③
R W B N
④
⑤
T2
T1
T20
T1
V
Instrument-panel potential sockets
To potential sockets on heavy-current bench
To "B" bench potential selector sockets
To "A" bench potential sockets
① Phase-shifter.
② Primary potential sockets.
③ Secondary " "
④ Secondary selector-switches 50V taps.
⑤ " " " 5-V taps.

FIG. 4.—A.C. test-set: voltage circuits.


Supply
R
W
B
N
1/200
1/40
1/20
1/10
1/5
1/4
1/4
1/2
Fine
Coarse
50 0α
100α
R W B N
RED
WHITE
BLUE
T2
T1
T7
T1
2.5
5
10
25
50
100
A B C D
T1 T3 T5 T7
T2 T4 T6 T8
E
F
T1
T2
To L.H. pair current binding posts on instrument panel
To current terminals rack "A"
To centre pair current binding posts on instrument panel
To current terminals rack "A"
To R.H. pair current binding posts on instrument panel
To current terminals rack "A"

Switches for regulation mounted as drawn.

FIG. 5.—A.C. test set: current circuits.

The indicating sub-standards used are of the single-phase dynamometer type. A feature of the wattmeters which does not appear to be commonly made use of is their voltage and current overload capacity: when deciding what voltage and current ranges the wattmeters being purchased are to have it is important to keep this characteristic in mind. A suitable choice often enables one to work at the upper end of the scale when otherwise this would not be possible.

For example, take the normal tests on a 5-ampere 230-volt single-phase meter. As the low-tension supply voltages on the author's undertaking are 400 and 230 volts, wattmeters having voltage ranges of 150 and 300 volts were purchased. One of the wattmeters used for this test has 2·5- and 5-ampere current ranges, and the other 0·5- and 1·0-ampere. The full-load test would be taken at 1 200 watts, which, with the 5-ampere wattmeter fields in parallel and voltage on the 300-volt range, gives a reading of 120 on a 150-division scale. For half load the voltage range is changed to 150, which gives the same reading. For quarter load the fields are connected in series, the voltage range being still 150, and again we have a reading of 120. For $\frac{1}{10}$ load we change over to the 1-ampere wattmeter, and with fields in series and a voltage range of 300 the reading is 120. For $\frac{1}{20}$ load we change over to the 150-volt range, and again the reading is 120. It will be appreciated that these results can be obtained in part when using the precision current transformers.

Thus in this test we have encountered a no greater instrument error than 0·34 per cent, if the instrument has an inaccuracy equal to 0·25 per cent of full scale, which is very unlikely at this point on the scale. The equipment was constructed by the author's staff, largely from components supplied by various manufacturers, at a cost of £276. Details of the components will now be given.

Current loading transformers.—There are three of these, each of 1 kVA capacity, with 10-ampere primary and secondary ranges of 2·5, 5·0, 10, 25, 50, and 100 amperes. In addition there are three of 3 kVA, with 10-ampere primary, and secondary ranges of 125, 250, and 500 amperes.

Voltage transformers.—There are three of these, each of 2 kVA, with 400-volt primary, and secondary tapped to give 9 steps of 50 volts and 10 steps of 5 volts, total 500 volts.

Phase-shifter.—This is of 1·5 kVA, and has a delta-connected stator and a star-connected rotor. The secondary line voltage and the primary line voltage are both 400 volts.

(3) Considerations Affecting the Design of Testing Equipment.

One of the most important problems to be solved in designing a.c. testing equipment is the provision of currents and their regulation, particularly with reference to wave-form distortion. The standard of reference is the sine wave, and unless the equipment is capable of supplying currents which are sinusoidal, or a very close approximation, it cannot be considered satisfactory. The more-commonly-used apparatus for current loading are current-loading transformers, used with primary resistance regulation; low-capacity power transformers, used with secondary resistance regulation; low-capacity power transformers, supplied from a multi-tapped auto- or double-wound transformer, sometimes with additional secondary resistance regulation; and low-capacity low-voltage alternators, often run in tandem, with one for voltage supply, the loading being controlled by varying excitation and direct resistance loading.

Current-loading transformers are simply current transformers; they behave as such, and generally they are designed in capacities varying from 0·5 to 3 kVA or higher. When used with primary resistance regulation they can be designed to have a number of secondary ranges, with the primary regulation having roughly the same effect on each range. Their primary and secondary connections are easily dealt with in any particular test-set lay-out, and they are silent, static, and cheap. The elimination of wave-form distortion is secured by the design and the method of use.

Low-capacity power transformers used with secondary resistance regulation suffer the disadvantage of difficult regulation. If it is desired to hold currents at various values, as is usual, variable resistance has to be included, and with a transformer arranged to supply loads from 0·01 to 100 amperes it will be seen that the provision of, say, 15 per cent variation at 0·125, 0·25, 0·5, 1·25, 2·5, 5·0, 10·0, 25·0, 50·0, and 100 amperes, must be costly. A further disadvantage is the varying voltage-drops in the apparatus under test. This makes it difficult to assign a ratio to a fixed resistance. It is quite common to have only one meter connected at one time, and 60 at another. When heavy currents have to be dealt with, the regulation difficulty is even more acute, and internal connections, i.e. those in the resistance bank, are often a source of trouble owing to temperature variation of the bank. In addition heavy switches are necessary for control, and the space occupied by a bank to load up from, say, 125 to 500 amperes at 6 volts is considerable.

The use of an auto-transformer or regulation transformer in conjunction with a small transformer is not economically sound, as it means having two transformers for the service that one will provide. Unless the regulation transformers have a very large number of tappings and are liberally designed some additional regulation will be necessary. A further disadvantage is their housing and connection arrangement.

Small alternators suffer the disadvantage that they are not static, are not silent or easy to incorporate in a lay-out which is required to supply conditions for widely differing simultaneous tests, and may not—over the range required—provide an output which is sinusoidal. For a given service the total equipment is very much more expensive than any other combination.

Primary resistance-regulated current loading transformers seem to possess the most advantages. When a current is passed through the primary of a current loading transformer, with the secondary closed through a burden, the secondary current produced is proportional to the primary current and the primary turns, and inversely proportional to the secondary turns. The secondary voltage will become that required to overcome the voltage-drop in the secondary circuit. This voltage will therefore be proportional to the impedance of the burden, and will vary with the secondary current. The secondary voltage is proportional to the core flux and to the exciting component of the primary current. The value of this component will be dependent on the transformer design, the impedance of the burden, and the current in the secondary circuit. The exciting component is not sinusoidal, and in flowing through the primary-circuit resistance will produce a non-sinusoidal voltage-drop in this resistance. The primary voltage will be distorted; the flux wave cannot then be sinusoidal, and the harmonic components will appear in both the primary and the secondary voltage-waves. The appearance of the harmonics in the secondary voltage-wave will result in their appearance in the secondary current-wave. The amount of distortion of the secondary current-wave is clearly dependent on the proportion of harmonics in the exciting component, and the ratio of load component to exciting component. It is possible, by suitable design and use, to make the ratio of load component to exciting component so high that any distortion which may be present cannot be observed by ordinary oscillographic inspection. The maximum flux density under worst operating conditions must be kept low. A figure of 5 000 lines per cm^2 would not be too high. A certain voltage will be required to drive a given current through a given burden. With the maximum density fixed it is possible to derive the core dimensions and primary and secondary turns. It is desirable to lay down a transformer with a volt-ampere rating considerably in excess of the estimated maximum, as the cost is not seriously increased by so doing.

It has already been shown that one of the most important factors in the design of the transformer is the voltage available at the secondary terminals for a given flux density, and the question arises how currents from, say, 0·01 to 100 amperes are to be supplied by the same transformer. It is not usually necessary to test the same number of heavy-current meters as, say, 5-ampere meters, at any one time, and it follows that heavy currents could satisfactorily be obtained from a winding having less turns than the low-current one. Consequently it is desirable to arrange for the transformer to have a number of secondary ranges, both from the point of view of economy and in order to enable one set of primary regulating resistances to be used, the regulation having roughly the same effect on each range.

In order to verify the above conclusions a shell-type transformer rated at 1 kVA was chosen. It has a 10-ampere primary, with a tapped and graded secondary giving ranges of 2·5, 5·0, 10·0, 25, 50, and 100 amperes. The corresponding numbers of turns are 61 to 240, 120, 60, 24, 12, and 6. The maximum number of 5-ampere single-phase meters which can be connected to each current-loading panel at any one time is 60, and the tests were begun with this number. The meters were connected in turn to the 5-, 10-, 25-, 50- and 100-ampere ranges (referred to below as the A, B, C, D, E, ranges respectively), and on each range the primary current was regulated so as to produce 5 amperes in the secondary circuit. The test data are given in Table 1 and Fig. 6, and the voltage and current waves in Fig. 7.

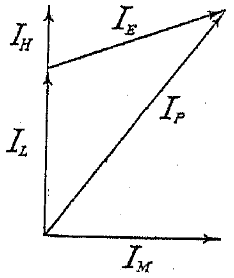


FIG. 6.

I_P = primary current. I_H = core-loss current.
I_M = magnetizing current. I_L = load current.
I_E = exciting current.

The wave-form is quite good until range D is reached, when distortion appears. The wave obtained on range E is very distorted; but this is to be expected with a load/exciting-component ratio of 0·284. Under operating conditions 5-ampere meters would not be connected to a range higher than B. It is interesting to compare

TABLE 1.

Range	Primary voltage	Primary turns	Secondary voltage	Secondary turns	Secondary current	I_P*	I_M*	I_H*	I_L*	I *	$\frac{I_L}{I_E}$
A (5-amp.)	volts 7·8	61	volts 10·6	120	amps. 5	amps. 9·88	amps. 0·13	amps. 0·05	amps. 9·83	amps. 0·139	70·7
B (10-amp.)	11·8	61	10·6	60	5	5·0	0·164	0·077	4·92	0·181	27·2
C (25-amp.)	28·0	61	10·6	24	5	2·11	0·244	0·129	1·967	0·276	7·13
D (50-amp.)	55·5	61	10·6	12	5	1·25	0·416	0·196	0·983	0·46	2·14
E (100-amp.) ..	117·0	61	10·6	6	5	1·86	1·72	0·216	0·492	1·733	0·284

* See Fig. 6.

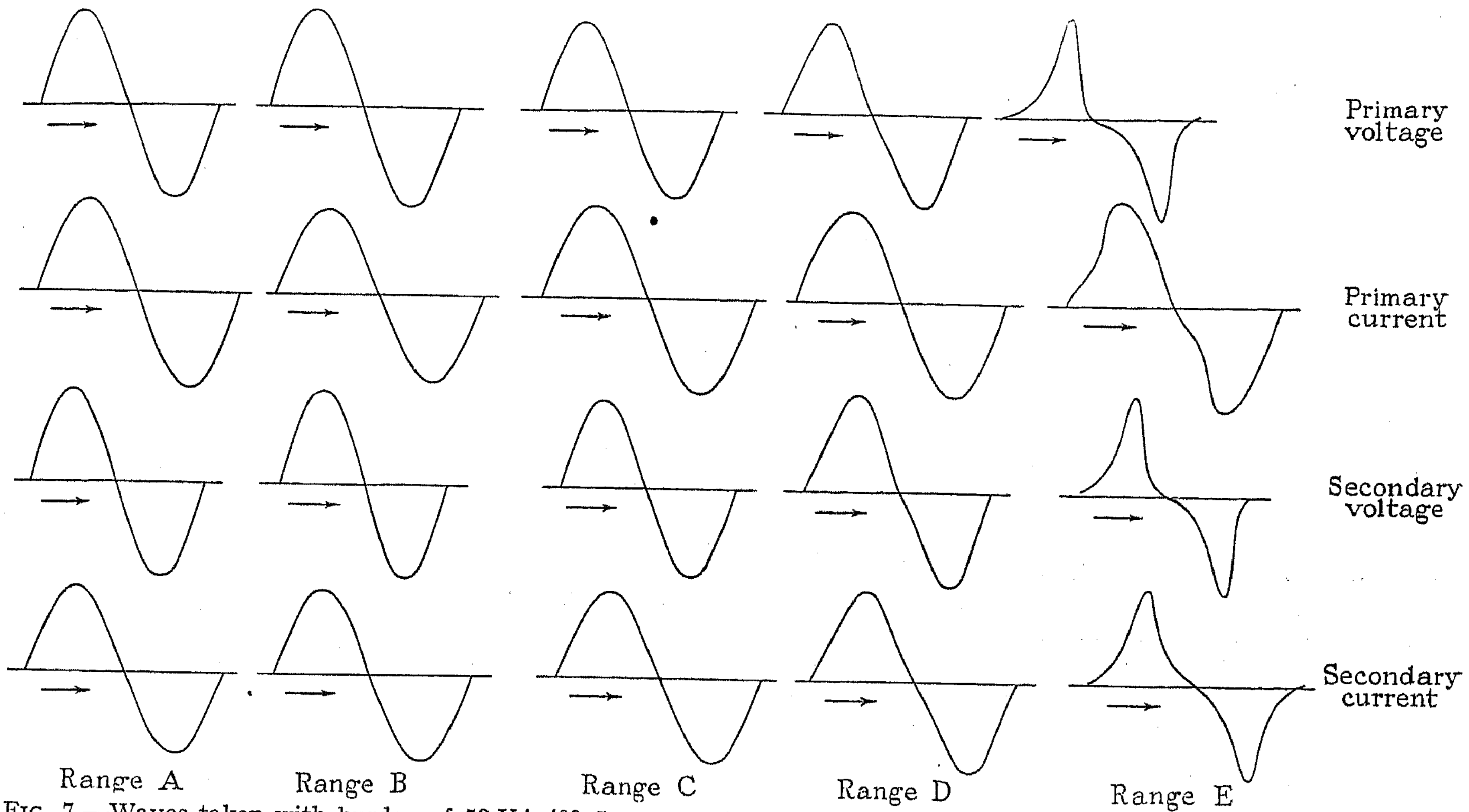


FIG. 7.—Waves taken with burden of 53 VA (60 5-ampere single-phase meters) connected to current loading transformer. Primary current adjusted to give 5 amperes in secondary circuit, on each range.

the waves obtained on range E (Fig. 7) with the waves shown in Fig. 8. In the latter case the 60 single-phase meters were connected to range E and loaded up to 5 amperes, and the secondary was open-circuited. Under these conditions the whole of the primary current is being used to magnetize the core. The primary resistance is constraining the current to a more sinusoidal form, and the result is the appearance of the harmonics in the primary and secondary voltage-waves. This is another way of looking at the effect of primary resistance with a loaded transformer; the resistance attempts to swamp the harmonics in the exciting component and thus constrain it to a more sinusoidal form.

The results of this investigation suggest that a 500-VA shell-type transformer designed for a flux density in the centre limb of 5 000 lines per cm² would be quite satisfactory for the work on which the 1-kVA transformer is used. The 1-kVA transformer is designed for a flux density of 12 000 lines per cm² in the centre limb when supplying a 1-kVA burden on any range.

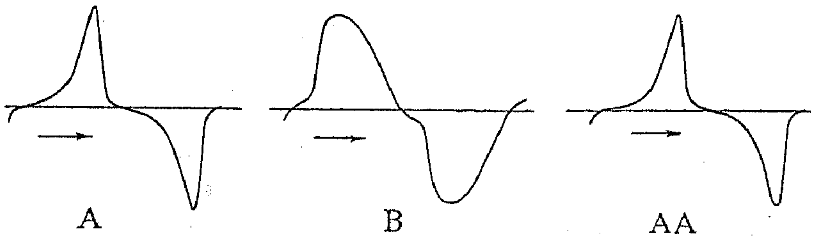
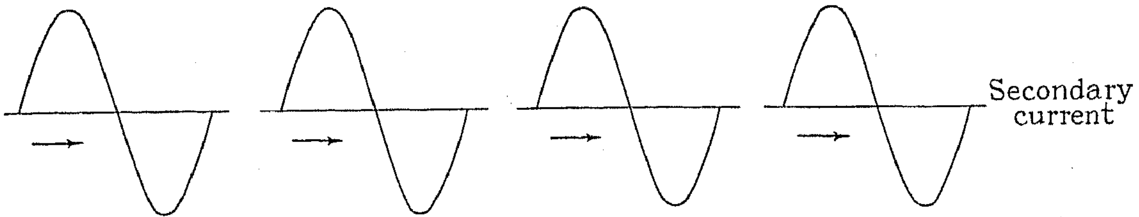


FIG. 8.—Waves taken on current loading transformer with open-circuited secondary, after primary resistance had been adjusted to give 5 amperes in secondary circuit.
A. Primary voltage. AA. Secondary voltage.
B. Primary current.

TABLE 2.

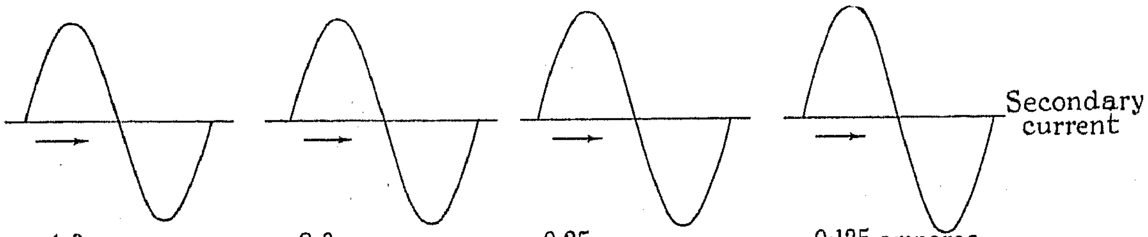
Range	Primary voltage	Primary turns	Secondary voltage	Secondary turns	Secondary current	I_P	I_M	I_H	I_L	I_E	$\frac{I_L}{I_E}$
	volts		volts		amps.	amps.	amps.	amps.	amps.	amps.	
A (5-amp.)	4·3	61	3·5	120	5	9·86	0·09	0·03	9·83	0·095	103·4
B (10-amp.)	4·7	61	3·5	60	5	4·98	0·108	0·059	4·92	0·123	40·0
C (25-amp.)	9·3	61	3·5	24	5	2·06	0·152	0·087	1·967	0·175	11·24
D (50-amp.)	18·0	61	3·5	12	5	1·1	0·198	0·1	0·983	0·222	4·43
E (100-amp.) ..	36·2	61	3·5	6	5	0·7	0·284	0·148	0·492	0·321	1·53

It has been mentioned earlier that an important factor is the voltage required at the secondary terminals for a given current; tests were made to illustrate the effect of a reduction in burden, and consequently in secondary voltage. A burden consisting of an ammeter, wattmeter, and one 5-ampere single-phase meter, was connected in turn to ranges A, B, C, D, and E. The test data are given in Table 2, and the secondary current-waves up to range D in Fig. 9. It will be observed that the wave obtained on range D is now quite good. This is due to the reduction in the impedance of the burden, and therefore in the exciting component.



Range A Range B Range C Range D

FIG. 9.—Waves taken with burden of 16·5 VA (ammeter, wattmeter, and one 5-ampere single-phase meter) connected to current loading transformer. Primary current adjusted to give 5 amperes in secondary circuit, on each range.



4·0 amperes 2·0 amperes 0·25 amperes 0·125 amperes

Range A

FIG. 10.—Waves taken with burden of 53 VA (60 5-ampere single-phase meters) connected to range A on current loading transformer. Primary current regulated to give currents shown, in secondary circuit.

The next test was made in order to examine the effect of a reduction of current in a given burden. The 60 single-phase meters were again connected to the 5-ampere range and tests were made with the primary current regulated to give 5, 4·5, 4·0, 3·5, 3·0, 2·5, 2·0, 1·5, 1·0, 0·5, 0·25, and 0·125 amperes, in the secondary circuit. Four of the waves obtained are shown in Fig. 10. The twelve waves are all equally good and demonstrate that although the primary load is dropping, the reduction in the secondary load calls for a progressively lower exciting component. It is not suggested that the load/exciting-component ratio remains the same at all loads. This can hardly be the case because of the shape of the normal B/H curve for ordinary transformer iron.

TABLE 3.

Range	Primary voltage	Primary turns	Secondary voltage	Secondary turns	Secondary current	I_P	I_M	I_H	I_L	I_E	$\frac{I_L}{I_E}$
	volts		volts		amps.	amps.	amps.	amps.	amps.	amps.	
C (25-amp.)	28·0	61	9·7	24	25·0	9·95	0·238	0·118	9·83	0·265	37·1
	7·0	61	2·4	24	5·0	2·03	0·133	0·058	1·967	0·145	13·5

In order to demonstrate further the suitability of this particular transformer, 100 25-ampere single-phase meters were connected to range C. The test data are given in Table 3, and the voltage and current waves in Fig. 11. Secondary-current oscillograms taken on the 3-kVA current loading transformer under normal operating conditions have proved to be as good as those obtained on the 1-kVA transformer.

Although, as has already been mentioned, the voltage transformers can be connected star/star if desired, to do so would only be permissible provided no secondary distortion was set up. The six waves (Fig. 12) obtained from the transformers mentioned above appear to be satisfactory. Theoretically, under all conditions a very small amount of distortion must, however, be present when primary regulation is used. To prove that this distortion has no effect on commercial accuracy tests, 9 5-ampere single-phase meters, all of different makes, were taken and tested first on the current loading transformer and then with pure resistance loading on a sinusoidal supply. From $\frac{1}{20}$ load to 100 per cent overload the difference between their performances on the transformer and on resistance loading was so small and variable that it was ascribed to personal, load-holding, and timing errors. These meters were connected to range E, together with 51 others, to produce the distortion shown in Fig. 7 (range E). They were then tested from $\frac{1}{20}$ load to full load with their voltage coils excited from a sinusoidal supply. Four of the curves obtained are shown in Fig. 13. These tests were carried out merely to show that, even with severe distortion of the current wave, the errors introduced are small. It has not been established that all the differences shown can be ascribed to the effect of distortion, as it is difficult to tie down differences of the order of 0·2 per cent.

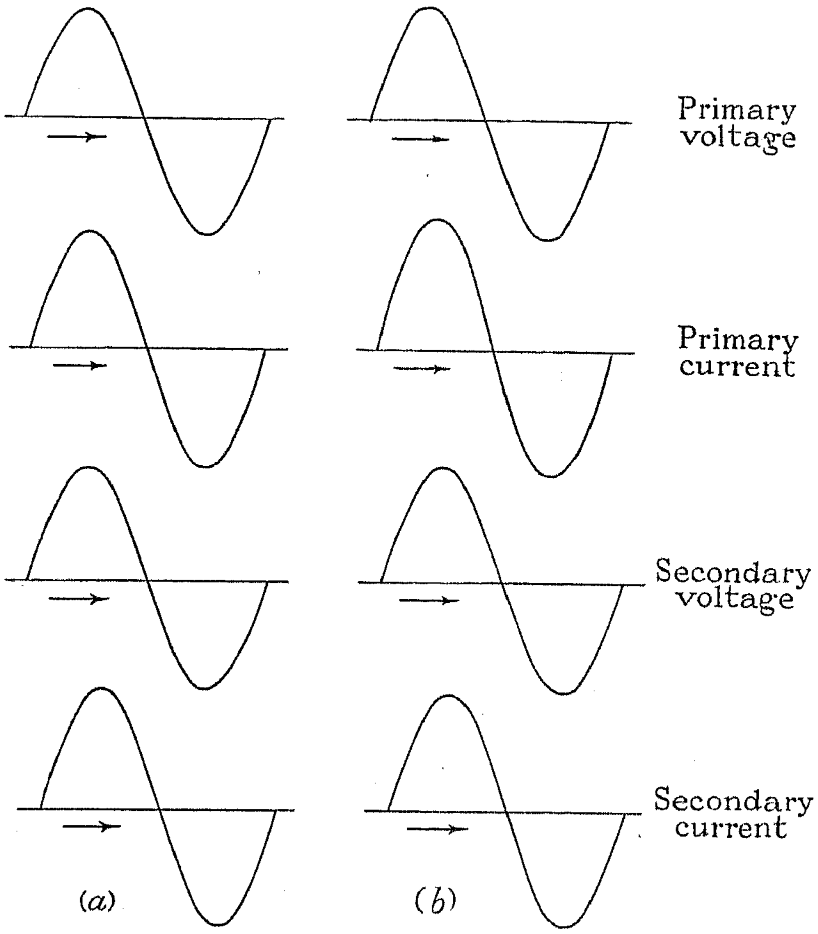


FIG. 11.—Waves taken with burden of 242·5 VA (100 25-ampere single-phase meters) connected to range C on current loading transformer. Primary current regulated to give:

(a) 25 amperes in secondary circuit.
(b) 5 amperes in secondary circuit.

(4) SPECIAL SINGLE-PHASE METER TESTS.

The improvement in electrical performance and mechanical construction of single-phase meters over the last 5 years has made it increasingly difficult for the supply engineer to assess the order of merit of the many different makes. The trend of low-capacity meter design would appear to be towards concentration on a good non-inductive load performance, together with minimum voltage-variation error. Tests of this nature are not very helpful for differentiation purposes, because of the similarity of the curves.

The adoption of the 2-part tariff by the undertaking with which the author is connected introduced the problem of finding a meter which was within the accuracy limits laid down in the appropriate British Standard Specification over a load range from 60 watts to 6 kW. Partly as a result of this demand an investigation was conducted to ascertain the effect on the curve of maintaining various loads for various periods. The results proved very valuable as a guide to electrical performance, and the method of testing has been adopted as standard for electrical-performance certification.

The meter under test has its pressure coil connected to a supply at rated voltage for 2 hours, this period being quite long enough to produce steady conditions on all makes available in this country. It is then loaded and tested in turn at $\frac{1}{20}$, $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, full, $1\frac{1}{2}$ × full, and 2 × full load at unity power factor. Soon after this test a curve

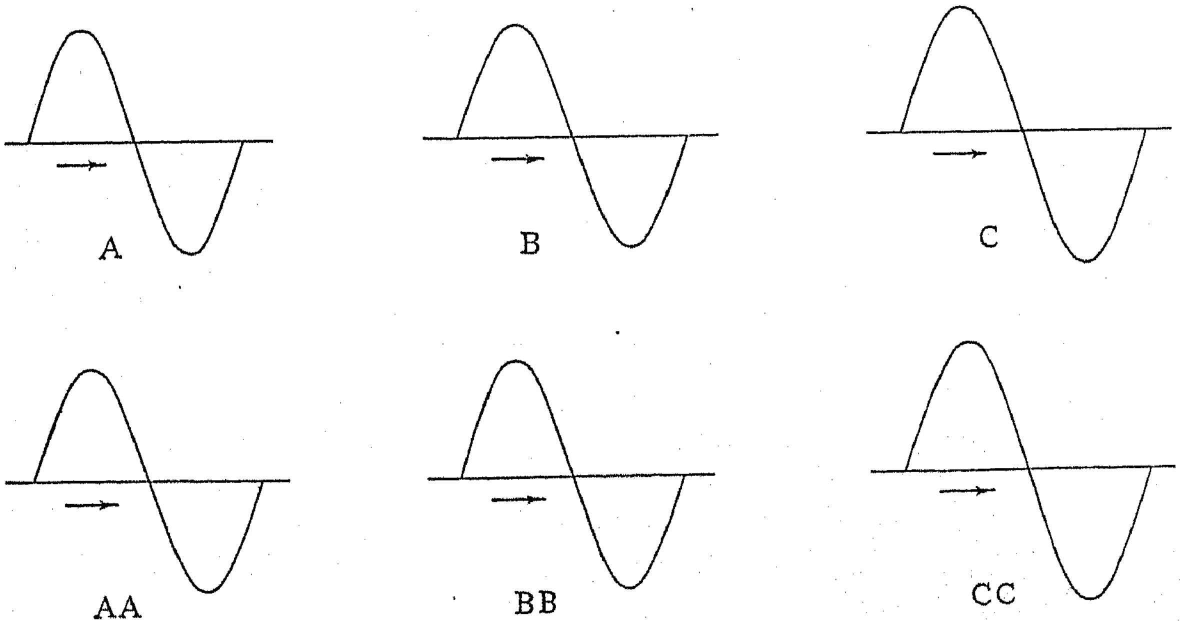


FIG. 12.—Waves taken on a star/star bank of voltage transformers.

A. Red/Neutral voltage, primaries connected to 250-kVA transformer, bank secondary neutral free.
AA. Red/Neutral voltage, primaries connected to 250-kVA transformer, bank secondary neutral earthed.
B. Red/Neutral voltage, primaries connected to phase-shifter, bank secondary neutral free.
BB. Red/Neutral voltage, primaries connected to phase-shifter, bank secondary neutral earthed.
C. Red/Blue voltage, primaries connected to phase-shifter, bank secondary neutral free.
CC. Red/Blue voltage, primaries connected to phase-shifter, bank secondary neutral earthed.

The pressure coils of 60 single-phase 230-volt meters were connected to the red phase and neutral for the A, AA, B, and BB tests. The pressure coils of 12 3-phase 3-wire 400-volt meters were connected to the red and blue phases for the C and CC tests.

is taken with the meter loaded in turn at $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, full-load, $1\frac{1}{2}$ × full-load, and 2 × full-load volt-amperes at 0·5 power factor. The meter is then run at full load for 2 hours and a further unity-power-factor test taken, starting at $\frac{1}{20}$ load. At the end of this test it is disconnected and left for at least 24 hours, after which it is again run at full load for 2 hours and a 0·5-power-factor test taken, starting at $\frac{1}{10}$ full-load volt-amperes.

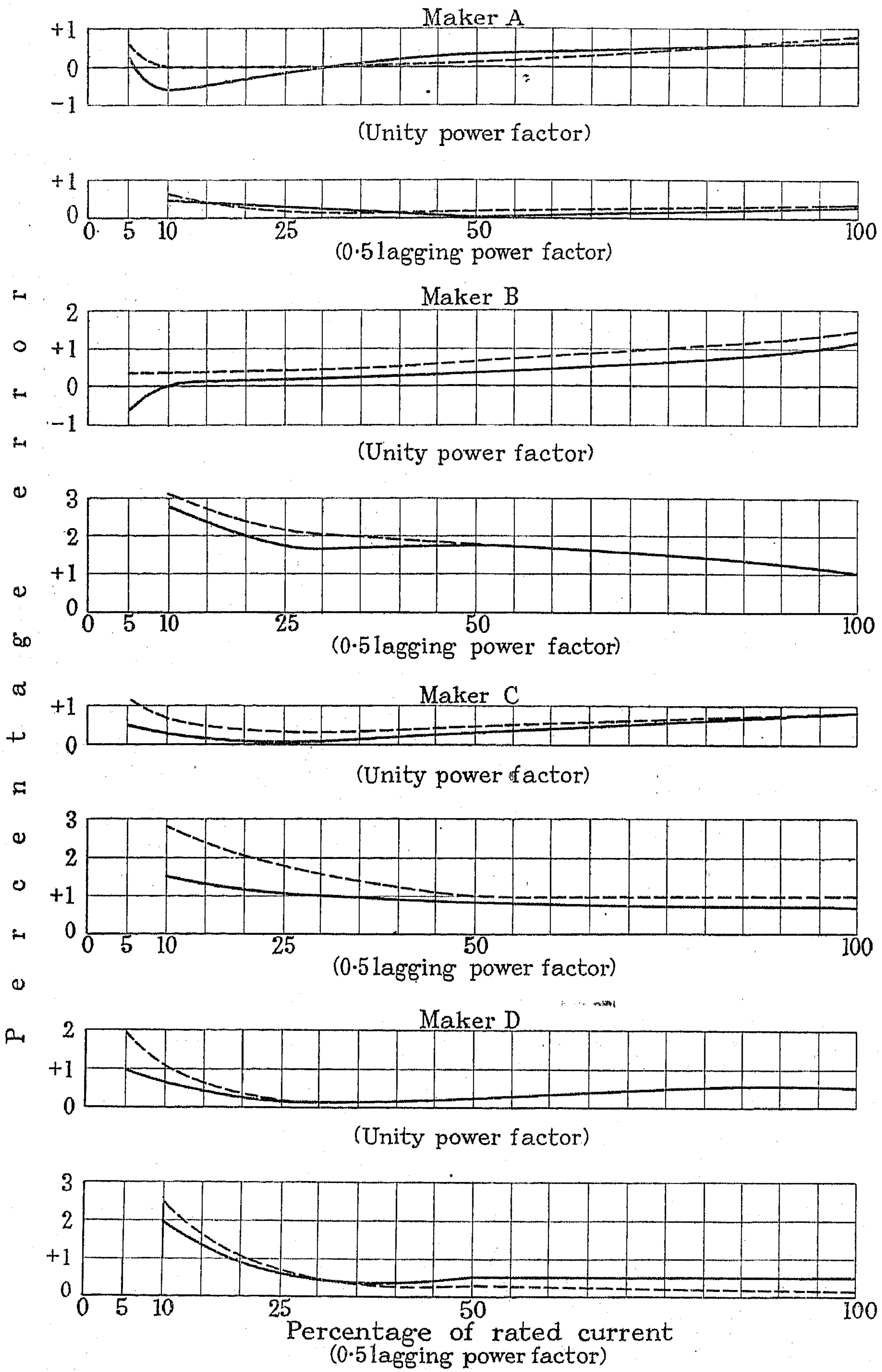


FIG. 13.—Curves showing results of tests with sinusoidal voltage associated with sinusoidal and distorted current.

——— Sinusoidal voltage and current.
– – – – Sinusoidal voltage and distorted currents (secondary current, range E, Fig. 7).

If the meter is well designed the four curves should lie close together. The four examples of these tests shown in Fig. 14 demonstrate that it is easily possible to differentiate between these meters from the point of view of electrical performance. The tests are a partial reflection of the effect of the temperature coefficient; the curve-shape change is reduced when the temperature of the whole of the meter is raised.

(5) SINGLE-PHASE METER TESTING.

The testing of low-capacity single-phase meters takes up a great deal of the time of the testing staff in the majority of supply undertakings. With regard to new meters, it has been found that one can expect from 5 to 20 per cent to arrive from the manufacturer with errors greater than ± 2·0 per cent at $\frac{1}{10}$ load and $\frac{1}{20}$ load. It is very unusual to find meters with an error greater than ± 2·0 per cent at loads higher than $\frac{1}{10}$. Experience of operation on circuit has shown that it is good practice to calibrate low-capacity single-phase meters to special limits, those adopted by the author being 0·5 per cent fast and 1 per cent slow at full load and 0·5 per cent slow and 2 per cent fast at $\frac{1}{20}$ full load. Most modern meters have a dip in their curve at about $\frac{1}{4}$ load, which is taken care of if they are calibrated to the above limits. It has been our practice for some time to test meters on site with specially-prepared check meters, or a rotating sub-standard meter, when complaints arise. Meters fixed on lighting circuits are tested on the lamp or lamps fitted in the room which is most used, on the total lighting load, and on an iron or vacuum cleaner (if the consumer possesses one). Meters fixed on heating circuits are tested on maximum and minimum available loads. We very rarely find a meter which has errors greater than ± 2 per cent when tested in this manner, although comparison with the original test records has shown that changes up to 1 per cent slower at $\frac{1}{20}$ load and 1 per cent faster at $\frac{1}{2}$ to full load take place even after so short a period as 12 months. This performance on circuit is the justification for the special calibration referred to above, and is to some extent responsible for the following conclusions with regard to methods of testing.

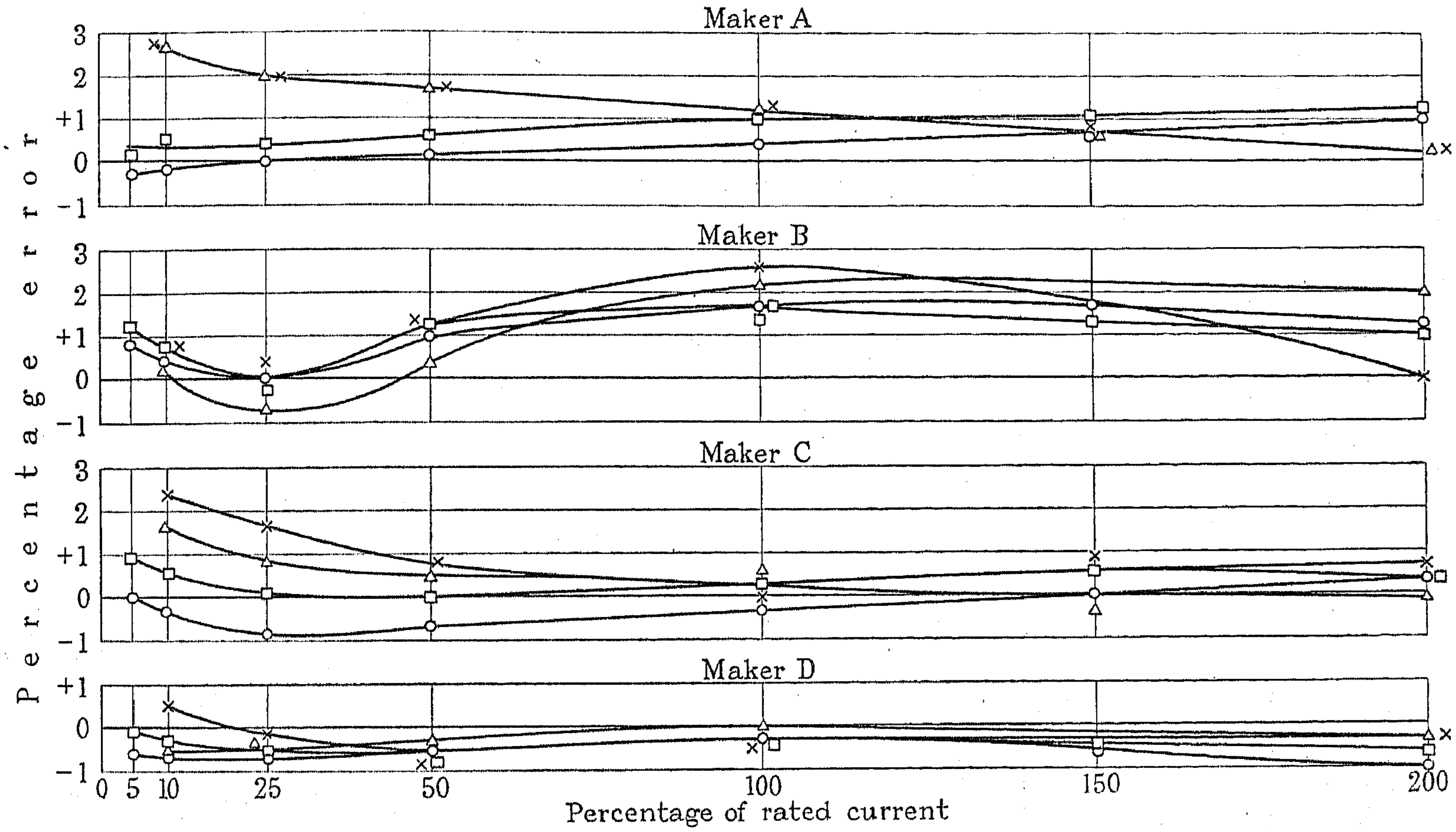


FIG. 14.—Curves showing results of series heating tests.

—○—○—○—○—○— Unity-power-factor test commenced at $\frac{1}{20}$ load with series coil cold.

—□—□—□—□—□— Unity-power-factor test commenced at $\frac{1}{20}$ load after running on full load for 2 hours.

—△—△—△—△—△— 0·5-power-factor test commenced at $\frac{1}{10}$ volt-ampere load with series coil cold.

—×—×—×—×—×— 0·5-power-factor test commenced at $\frac{1}{10}$ volt-ampere load after running on full load for 2 hours.

The three methods in general use are testing by timing on loads held at given values, revolution testing with a rotating sub-standard meter, and dial testing with a specially-prepared meter. If the revolution method is used on meters with covers made of magnetic material, it is necessary to fit special cut-away testing covers. These covers enable rotor spots to be set, gauges to be inserted, and adjustments to be made. With case-cover design and dimensions changing as rapidly as they have done during the last few years, the necessity for cut-away covers is a serious disadvantage of this method of test. Moreover it is generally at low loads that adjustments have to be made, and with gauges marked in tenths of a revolution the minimum number of revolutions which can permissibly be run on, say, $\frac{1}{20}$ load is **10**; which makes 1 division on the gauge equivalent to 1 per cent. The procedure of running 10 revolutions at any speed from 0·9 to 2·4 r.p.m. may have to be repeated many times during calibration, and this is a serious disadvantage. Our experience of the dial method of testing has been disappointing. Although when once connected the meters test themselves, as it were, the time taken to maintain the standard meters in satisfactory condition is appreciable. When adjustments have to be made, either the timing or the revolution method has to be resorted to, with a further dial-run on the re-calibrated meters. In addition, the time taken to get a reliable reading on $\frac{1}{20}$ load may be 12 hours or more, and, for the sake of economy in time, tests at low loads are usually carried out during the night. This means that the testing equipment has to be alive when there is no one in attendance, which is not good practice. From all points of view, the best method to adopt in connection with new meters is that of timing on held loads. Except in the case of a major repair, such as the replacement of a voltage or current electromagnet, repairs to a.c. meters are carried out as far as possible in such a manner that the various adjustments are left in the same positions as they had when the meter was removed from the circuit. If this practice is followed very little adjustment has to be made later. Here again the timing method is used, and has proved to be most successful. Were it not for the night non-attendance disability, arrangements would be made to amplify the timing test on $\frac{1}{20}$ load by a dial test. If variable friction were present, such a test would show it up. Experience has shown, however, that such amplification is not imperative. After the timing tests have been carried out the meters are given a short dial-run on a held load to check the train gearing. A starting current and over-voltage creep test completes the testing.

	Full load	½ load	¼ load	$\frac{1}{10}$ load	$\frac{1}{20}$ load
Red and blue elements	1·0 −	O.K.	O.K.	O.K.	0·17 +
Red element only	0·33 −	0·17 +	O.K.	0·5 −	0·5 +
Blue element only	0·17 +	0·5 +	0·5 +	1·0 +	1·7 +
Red and blue elements	0·5 −	0·17 +	0·33 −	0·33 −	—
Red element only	0·33 +	0·67 +	1·2 −	O.K.	—
Blue element only..	0·33 +	0·5 +	0·56 +	1·2 +	—
Red and blue elements	0·86 −	0·44 +	O.K.	0·15 −	O.K.
Red element only	0·14 −	0·73 +	0·3 −	0·6 −	O.K.
Blue element only..	0·29 +	0·58 +	0·74 +	0·6 +	1·2 +
Red and blue elements	0·29 +	1·4 +	0·37 +	0·75 +	—
Red element only	—	—	—	—	—
Blue element only	0·29 +	0·87 +	0·99 +	1·0 +	—
Red and blue elements	0·5 −	0·67 +	0·5 +	0·5 +	1·2 +
Red element only	0·33 +	0·67 +	0·33 +	0·5 +	1·5 +
Blue element only..	0·84 +	1·2 +	1·2 +	1·7 +	2·7 +
Red and blue elements	1·2 −	0·33 −	0·66 −	0·33 −	—
Red element only	2·0 +	2·4 +	0·84 +	1·5 +	—
Blue element only..	2·1 −	1·8 −	1·5 −	1·0 −	—

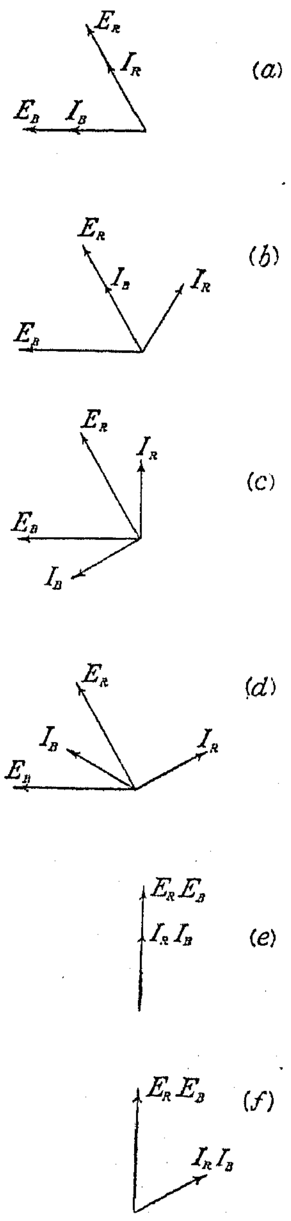


FIG. 15.—Results of tests on a 3-phase 3-wire unbalanced-load type of meter. The voltage and current phase relationship which existed for each of the tests is shown immediately to the right of the tabulated results.

(6) THREE-PHASE METER TESTING.

In 1927 a paper was read by Mr. O. Howarth* before the Electrical Power Engineers' Association in which the results of a novel method of testing polyphase meters for interaction were outlined. It would be a great advantage if this method were adopted by manufacturers as a standard performance test, as it would not only lead to an improvement in the accuracy performance of polyphase meters but would also provide a standard test for interaction. Unfortunately this method of test cannot be used to predict on-circuit performance in terms of percentage error, against single-phase calibration. Owing to the presence of interaction, polyphase meters should be tested under polyphase conditions. It is not practicable, however, to calibrate a 3-phase 3-wire meter under polyphase conditions. For example, under unity-power-factor balanced-load polyphase-circuit conditions the power factor on each element is 0·866, and the adjustment applied would have to be a combination of braking and quadrature. The method of calibration and test devised by the author is as follows:—

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* *Electrical Power Engineer*, 1927, vol. 9, pp. 19 and 57.

The test-set voltage transformers are connected delta/star and have their primaries excited from the phase-shifter. This condition gives us a 3-phase 4-wire supply to the test-room voltage circuits, the phase relationship of which, with respect to the 3-phase 4-wire supply to the current selection panel, can be varied from unity power factor to zero lag or lead. The phase rotation of both supplies is red, white, blue. The red-element pressure coil is connected to red and white, and the blue-element pressure coil to blue and white, on the voltage supply. These voltages therefore have the same phase relationship as exists when the meter is on circuit. The red-element current coil is connected to a current loading transformer the primary of which is, at the outset, connected to red and white on the current selection panel. The blue-element current coil is similarly connected to blue and white on this panel. With the phase-shifter set to unity, the current and voltage on each element are in phase and the blue-element voltage and current are leading the red-element voltage and current by 60° (Fig. 15*a*). The meter is calibrated under these conditions at full, $\frac{1}{2}$, and $\frac{1}{4}$ load, or $\frac{1}{5}$, $\frac{1}{10}$, and $\frac{1}{20}$ load; first with the blue element loaded, then with the red element loaded, and finally with both elements loaded. The pressure coils are left connected the whole of the time. For inductive-load calibration the phase-shifter is moved to produce the condition shown in Fig. 15(*b*), which gives 0·5 power factor on each element. It is calibrated at full-load volt-amperes and tested at $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{10}$ full-load volt-amperes, first on the blue element, then on the red element, and finally with both elements loaded. This completes the calibration of the meter. For the polyphase check the phase-shifter is restored to unity, and the primaries of current loading transformers are connected to red and neutral and blue and neutral respectively (Fig. 15*c*). This condition gives 0·866 lag on the red element and 0·866 lead on the blue element, which is the 3-phase 3-wire circuit condition for a unity-power-factor loading. The tests at the points outlined above are repeated, but no attempt at adjustment is made. For the final test, the phase-shifter rotor is moved to a position which gives zero power factor on the red element, and a test is made first with load on the red element and then with it disconnected. To check for zero, the pressure coil of the red-phase sub-standard wattmeter is connected first to red and neutral and then to white and neutral. If in each case the wattmeter reads volt-amperes divided by 2, the phase-shifter setting is correct.

The test results obtained on a 5-ampere 200-volt 3-phase 3-wire meter of well-known make are given in Fig. 15. It is clear that this particular meter could be calibrated single-phase, or in the manner described above, to produce the particular polyphase calibration shown. It would, however, be essential to examine its interaction performance on the lines outlined in Fig. 15 before calibration on a single-phase supply was attempted, in order to arrange for the special calibration of each element. The necessity for this special calibration is the chief disadvantage of single-phase testing. If the method described above is used, the two elements can each be adjusted to be as closely accurate as possible on both the unity-power-factor and the 0·5-power-factor tests, without examination of the interaction performance being necessary. The meter used for the tests outlined in Fig. 15 suffers very badly from interaction, and was specially chosen for this reason. Meters with less interaction show a much better polyphase response to the method of calibration outlined.

An inspection of Figs. 4 and 5 shows that it is very easy to make the necessary test-circuit changes, and it is better to calibrate in this manner than single-phase. The difference in percentage errors between the calibration test and the polyphase check can be readily catered for, once the particular design characteristics are known. The allowances which have to be made during calibration are very regular for any given design.

The author wishes to express his indebtedness to Mr. F. L. Ogden, borough electrical engineer to the Oldham Corporation, for permission to publish data relating to the Meter Department, and for the facilities granted to him during the preparation of this paper.

Discussion before the Meter and Instrument Section, 5th January, 1934.

Mr. E. J. Riordan: I do not agree that the "best method to adopt in connection with new meters is that of timing on held loads." My own experience suggests that dial testing is superior: it is more stringent and it effectively reveals faults, especially on low loads. Referring to the dial testing of new meters, a test extending over several hours on full load and also on low load is far superior, and it is being adopted by large electricity supply authorities. From an efficiency point of view, there is no doubt that the labour required on testing is much less and the results over a long period are bound to be better than those of a short-period run, such as 10 minutes' or a quarter of an hour's timing on the timing test. Dial testing as a whole approximates more closely to the actual conditions under which the meters ultimately operate. The author's statement that the proportion of reject meters which have to be re-tested is as high as 20 per cent, is somewhat exaggerated; in my opinion 5 per cent would be a more approximate figure, and such a value would not seriously handicap the long-time dial testing.

Mr. J. S. Buckley: I should like to show a few slides illustrating some of the methods of meter testing in use abroad. (Mr. Buckley here exhibited a number of lantern slides.) In the U.S.A. an artificial load, called a phantom load, is used for testing meters on consumer's premises. This system of testing has the advantage that it avoids the necessity for regulation of the load, which is essential in the wattmeter method. A rotating standard is employed in which the main pointer is fixed on the spindle of the disc; and the dial is graduated in tenths and hundredths of a revolution. The 1-ampere series coil has a fuse protecting it against accidental short-circuits or overloads, and there is also a device for re-setting to zero after each test. Stopping and starting is carried out by means of a button switch on a length of flexible wire. When the shunt circuit is opened a breaking device on the disc stops the latter immediately; its operation compares very favourably with that of the stopping and starting of a stop-watch. This standard way of testing enables one to compare revolutions against revolutions, and the method has proved very successful as it eliminates the necessity for an assistant to steady the load. It can be used for testing meters in batches. A test bench that I used for this kind of testing had a special device on it, with spring contact studs, which enabled the meters to be put in circuit without any disconnecting of the shunt bridges. The potential was supplied from a transformer with a number of secondaries, according to the number of meters on the test bench, the loading being done in a similar manner by means of fixed resistances on the secondary of a low-capacity power transformer. It was considered sufficient to test the meters at unity and 0·5 power factor. I had a similar kind of board or test bench built up to do the 3-phase testing, but the rotating standard was always used. This was kept in condition by installing in the test room an ordinary service meter, and the tester could at any moment check the rotating standard and determine whether it had moved off the calibration curve. If any change was noted it was sent back to the laboratory for checking against the master standard; this never left the laboratory, and was always in good condition. The testers are able to test and calibrate on site 12 meters each per day, and I have known some who have tested 16. The tester takes off the train of the meter to check the ratios. The results of the tests are recorded on certificates, which are kept for future reference. I think the rotating-standard method which I have just described is preferable to any other from the point of view of a supply undertaking, and it has proved entirely satisfactory with a supply company having 90 000 a.c. and 25 000 d.c. meters, 60 per cent of the first-named being of British manufacture.

Mr. H. S. Petch: I agree with the author as to the desirability of testing transformer-operated meters with and without current transformers. As few test rooms possess facilities for checking voltage-transformer inaccuracies it would be helpful if manufacturers would make a regular practice of furnishing definite test data with voltage transformers, instead of merely stating that they conform to the appropriate British Standard Specification. The author's record of his investigations into the suitability of primary resistance-regulated current loading transformers is very interesting, and I think his conclusions are correct. I recently had to consider the same problem, but with the added complications of heavier currents and of dual frequency. These added difficulties led to the decision that owing to the size and cost of transformers of sufficiently low flux-density the author's method would be uneconomic. The arrangement shown in Fig. A was therefore devised, and has worked very well. The 230-volt supply is connected to a transformer, of which the 10 secondary sections develop about 2 volts each and can be connected either in series or in parallel The low-voltage current, having passed through the apparatus on test, is again stepped back to 230 volts by a second, similar, transformer, and the load resistance is connected across the 230-volt side of the latter. A number of different loads can be obtained by interconnecting the 10 sections. The sub-standard current transformer used for measurement carries the whole of the low-voltage current, however the sections are arranged, and one can test a meter at several loads without changing the resistance values or the wattmeter readings. The control board and transformers form a 3-phase bank, giving a maximum of 1 200 amperes per phase, and the whole of the heavy-current equipment is contained under or on a small table. The entire apparatus occupies only about 35 sq. ft. It seems to me that in the author's arrangement, if the secondary circuit of the 2½-ampere range became open-circuited, a voltage exceeding 1 000 volts might develop; if so, it might be well to take some precautions to protect the operator.

Mr. S. Hunt: I should like to refer to our "mass-production" method of dial testing. We have 4 test-sets similar to those mentioned by the author, and 40 meters are connected in a batch, the loads being put on the meters for various periods. The same registration is required on the dials for every test; that is to say, if we run for 10 minutes at full load we have to run for 100 minutes at $\frac{1}{10}$ load, and so on. I have only three assistants helping me, and last year we tested 8 826 a.c. meters and 4 500 d.c. meters, or 13 326 altogether. The advantage of this method is that, when the test sets are running for any length of time, the operator can leave them and devote his attention to work in some other part of the test room. It is important, however, to get the values quickly. I always employ as standard two rotating meters, preferably of the same make as the one we are using, fitted with large dials and counter-weighted pointers. On one I impose the advance and on the other obtain a check reading. For many years when carrying out d.c. meter testing we always had a meter in circuit that was tested by the local testing authority, and we claimed that practically all our meters were tested under the local testing-authority's conditions; because on the first calibration test the current went through the meter that was tested by the local authority. I hope to do the same thing with a.c. meters. One of these pairs of meters to which I have referred will be tested and sealed by the local testing authority. Reverting to our method of a.c. meter testing, when we want a heavy load, such as 50 or 100 amperes, we move an ordinary porcelain fuse-block from one position to another, thus inserting two heavy current-carrying meters in circuit together with the ammeter on the primary side of the set. We take the full-load reading of the ammeter and then impose the advance we require. When the meter reads what we want it to, we switch off. For a meter of small size we make the advance 0·25 kW; for a 50-ampere meter, 2½ kW; for a 100-ampere meter, 25 kW; and so on. Last year we tested roughly 260 meters per week, on the basis of 52 working weeks to the year, a wonderful performance for only two testers. Of the disputed meters sent to my local testing authority for testing, 70 per cent are proved to be accurate, and the others are only from ½ per cent up to a maximum of 2 to 3 per cent outside the tolerances allowed. The same idea is adopted in connection with power-factor testing. I have asked the manufacturers to supply me with a meter so arranged that it stops dead at 0·5 power factor. My testers then put their power-factor load on; when they put iron in the circuit the disc revolves one way, and when they put resistance it revolves the other. The test set is checked against the standard wattmeter, which is itself checked periodically. I think my remarks have made it clear that dial testing is far quicker, far better, and will show up bad train gearing qualities to a greater degree than revolution testing.

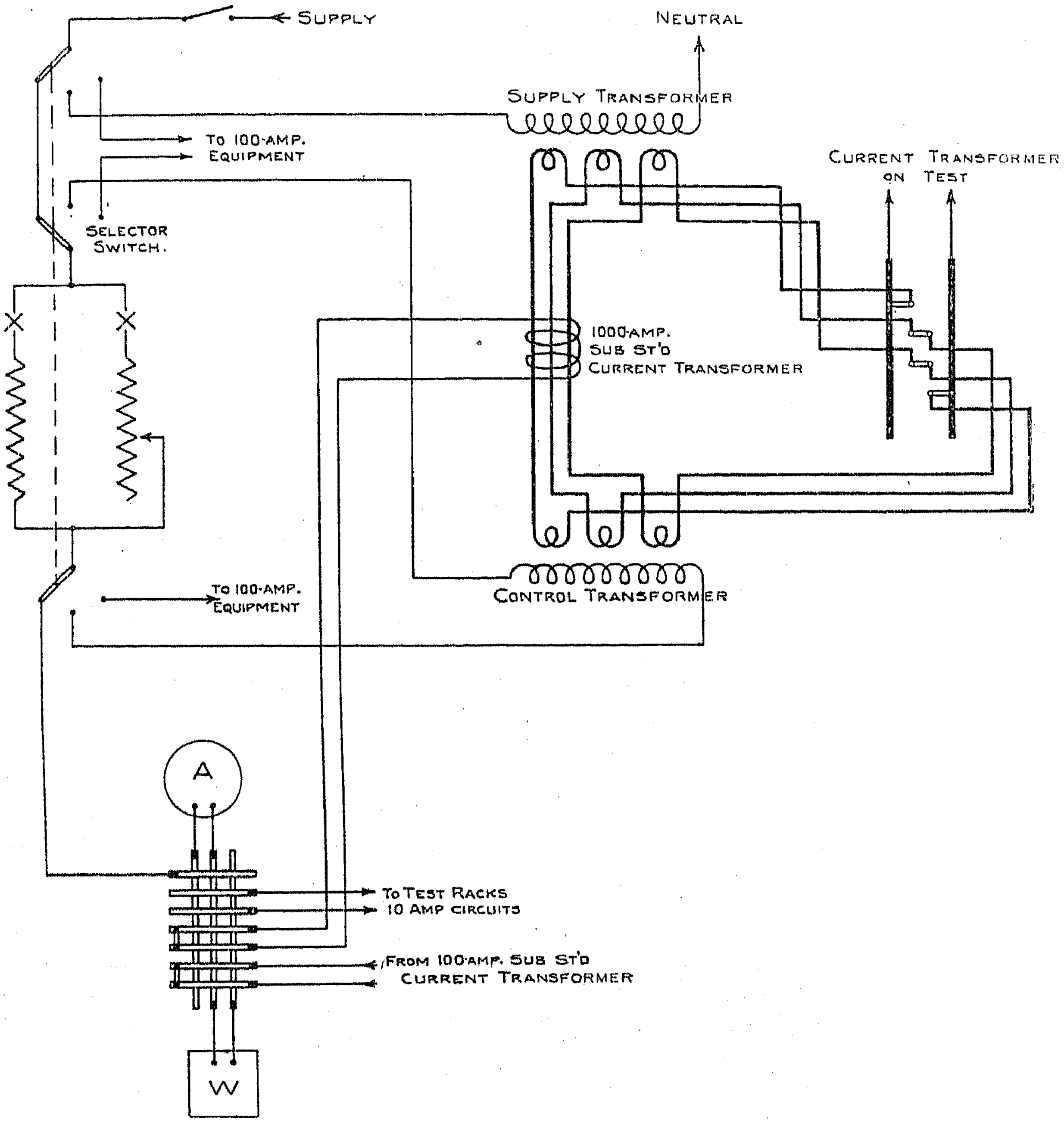
Supply
Neutral
Supply Transformer
To 100-Amp. Equipment
Selector Switch.
Current Transformer on Test
1000-Amp. Sub St'd Current Transformer
To 100-Amp. Equipment
Control Transformer
A
To Test Racks 10 Amp circuits
From 100-Amp. Sub St'd Current Transformer
W

Fig. A.

Mr. O. Howarth: The paper pays little attention to 4-wire 3-phase testing, which is rather more difficult than 3-phase 3-wire testing. With regard to the author's wattmeter, when changing the range of this, one has to take leads off and put them on different terminals; this is a slow method compared with that of making the changes by means of ordinary link switches. I should like to ask whether the cost of £276 mentioned on page 45 includes the outlay on instruments and current transformers. Dealing with the regulation of the current, the author states that the use of an auto-transformer or regulation transformer in conjunction with a small transformer is not economically sound. I do not agree. If an auto-transformer is used to supply the current loading transformer, with a resistance in between them, the cost of the resistance is reduced very considerably, and the difference may readily cover the cost of the auto-transformer. Perhaps the greatest advantage of depending upon resistance is the fact that it ensures a satisfactory current wave in the testing circuit. I should like to stress the fact that it is legitimate to put resistance in the primary circuit of the transformer in order to regulate the current, provided the transformer is suitable. I congratulate the author upon the thoroughness of his proof of this. In Section (5) he refers to the testing of meters by the revolution method and the difficulty encountered when covers made of magnetic material are used. We find it is a decided advantage to have the covers of meters made of non-magnetic material. There is no objection to doing this so far as the ordinary a.c. meter is concerned, because it is unlikely to be installed so near a heavy-current cable that it is affected by the stray field from the latter. Dealing with the dial testing method, I think the relative cost of the various methods depends very much on the accuracy limits allowed. If an accuracy of 1 per cent is insisted upon, the method of testing will probably be very different from what it would be if one were prepared to allow 2 or $2\frac{1}{2}$ per cent, and a difference of 0·5 per cent in the limits allowed may easily make it more economical to test by the stop-watch method than by the dial test or the revolution method; and in any event if there are many adjustments to be made the other methods are undoubtedly clumsy. Making an adjustment and then waiting several hours to find out whether it has done any good or not is a slow business, and I think that meter engineers who adopt such methods allow wide limits of error, or alternatively revert to the stop-watch method when they want to make adjustments. Turning to the subject of polyphase-meter testing (Fig. 15), I think the author's tests are more complete than they need be. Our custom is to test the two elements separately under conditions (*a*) and (*b*), and both elements loaded under conditions (*c*) and (*d*). Most of the meters which we handle are of the 4-wire type, and it is therefore necessary to test 3 elements instead of 2. I am glad to have the support of the author for the method of testing meters by timing against stop-watches. We carry out about 10 000 meter tests each year by means of stop-watches, and by our system of exchanging duties amongst the members of the department we are able to avoid keeping anyone too long at the work of revolution counting or " watt watching."

Mr. F. E. J. Ockenden: I am not in favour of the author's method of increasing the sensitivity of wattmeters by putting more than the normal voltage across the terminals of the instrument. This is permissible only when the instrument has a press-key and is well damped; so that one can press the press-key, take a reading quickly, and release it again. The author's second method of increasing sensitivity I approve of still less. He says in Section (2), " For $\frac{1}{10}$ load we change over to the 1-ampere wattmeter." It is not likely that the wattmeter will take less than 3 VA on the current side, and this is equivalent to a 300-VA burden on the 7·5-VA transformer with which he conducts the tests. When using current transformers it is fatal to try to increase the sensitivity by the use of low-reading instruments, because their volt-ampere consumption is relatively high. The only safe method is to change the primary range of the transformer, leaving the normal instrument connected to the secondary. The symbols in the author's vector diagram for the transformer are non-standard. He uses I_H for core-loss current, which is usually represented by I_L, and I_E for exciting current, whereas it is more usually denoted by I_O; the magnetizing triangle then being I_O, I_M, I_L. Is not he in error in the last column of Table 1 in taking as his factor of excellence the ratio of I_L (the load current) to I_E (the exciting current)? Actually, I_E is formed of two components, I_M (the true magnetizing current) and I_H (the core-loss current). The latter, like the load current, has a sinusoidal wave-form, and the only disturbing factor is I_M, the true magnetizing current; so that it would be more accurate to take as the ratio I_L/I_m, i.e. the load current divided by the true magnetizing current, the latter being the only non-sinusoidal component of the exciting current. With regard to the question of voltages on open-circuited current transformers, the r.m.s. voltage across the open-circuited terminals of a current transformer may not amount to very much. It is easy to estimate the average voltage from simple considerations of frequency, the known saturation flux-density of the core, and the number of turns. The r.m.s. voltage in any given conditions will hardly rise to more than 3 times the average voltage; in other words, if from the saturation flux-density of the core one calculates the average voltage and multiplies by 3, one has the maximum r.m.s. voltage. The peak voltage, however, may rise to any value. I have met with cases (measured with a special contact-maker) where the peak voltage has risen to 20 times the r.m.s. voltage, and it is the peak voltage which punctures the insulation. Any method of testing which involves open-circuiting current transformers exposes both the operator and the insulation to considerable hazard.

Mr. E. S. Ritter: On pages 42 and 53 the author refers to " zero lag " and " zero lead "; should not this be " 90° lag " and " 90° lead," or " 100 per cent lag " and " 100 per cent lead "? When a number of meters are connected with their current coils in series they have an inductive characteristic; would not they shift the phase of the testing current with respect to voltage, and lead to error? For example, it might be presumed that the test was under 100 per cent power-factor conditions when actually the value was 90 per cent. There are many cases nowadays where the current wave-form is anything but a sine wave, and I should like to ask the author how he knows that the meters read correctly under non-sinusoidal-current conditions. With regard to the counting of revolutions, could not photo-cells be used for this purpose? In dial testing, could not the dials be read photographically? Recently the proposal has been made, and apparatus devised, to photograph a number of meters (in telephone exchanges) which are small and close together so that the meters should all be read simultaneously, thus eliminating any possibility of an error in the reading. Could not some similar method be adopted for reading the dials of meters in the test room? In Fig. 14 the meter of maker D seems at first sight to be very much better than that of maker A, but on closer inspection it appears that maker A's meter has not been properly adjusted on the 0·5 power-factor load. I suggest that the latter is not so bad as it seems to be, as for the two 0·5 power-factor tests the points lie one on top of the other, whereas for maker D's meter they are divergent, at any rate at low percentages of the rated current. If the power-factor correction of maker A's meter at low loads were made better, this meter would be more in line with that of maker D.

Mr. G.F. Shotter: In Section (3) the author states that low-capacity power transformers suffer the disadvantage of difficult regulation. I cannot say that I agree with the author in this, as I have not met with such a difficulty. An arrangement using a transformer with a multi-tapped secondary in conjunction with five or more set resistance loadings, to correspond to the various sizes of meters under test, has been found to be both flexible and satisfactory for single-phase testing of meters with rotating standards. The lay-out of such an arrangement is shown in Fig. B (page 58), which gives the current connections of a bench fitted in this manner. Another arrangement, which gives even greater flexibility, makes use of a tapped secondary and employs a carbon rheostat as control. This carbon rheostat is sectionalized into 16 sections by means of suitable single-pole change-over switches. These, in conjunction with mechanical pressure control, give a range of practically 5 000 to 1. I think the author is to be congratulated upon having demonstrated how far it is possible to go with primary control. Possibly in some testing this has advantages, but I still think that for meter testing it is safer to keep to secondary control. I am in agreement with the author that the most satisfactory way to test meters is either by timing on held loads or else by means of a rotating standard. I do not think that any advantage either in speed or in accuracy at low loads is obtained by dial testing methods using a prepared standard. My experience is that variations in friction in the meter are less likely to be noticed when using the dial test method than when using the timing or rotating-standard methods. It should be realized that a long-time low-load dial-run only gives the mean error, and, although it is possible for the friction to vary considerably during the time of test, the result—depending upon the setting of the meter—may still be apparently satisfactory. Obviously, no method of testing will show up high friction if it has a constant value over the testing period. I am, of course, not referring in this case to a dial-run for the purpose of checking the train. With reference to the author's statement about the use of ferrous covers (Section 5), I should like to point out that some meters have been found to be affected at low loads even when fitted with non-magnetic covers. That is, their calibration is different with the cover on from what it is with the cover off.

Mr. R. S. J. Spilsbury: I am interested in the author's remarks on the various methods of calibrating meters. In a standardizing laboratory, meters of any type may have to be tested, and the speed of the fastest-running dial may be such that days would be required to make a satisfactory dial test at a low load: further, only one or two meters are usually tested at one time. Under these conditions the method of timing the meter on loads held at given values, supplemented by a gearing test at a high load, has overwhelming advantages. The conditions met with in the test department of a supply authority are very different, and it is interesting to find that the author considers the timing method to be the best solution in this case also. There seems little doubt that such a method gives the highest accuracy, since the other methods introduce a transfer meter, and any variation in the performance of this meter will appear in the result. Objections which can be raised against the timing method are the tedious nature of the counting operation and the possibility of errors in counting. These troubles can be overcome by the use of an automatic counter embodying a photoelectric cell. A device of this kind, due to Mr. A. Felton, has been in use at the National Physical Laboratory for some time. The apparatus, which has been described elsewhere,* employs amplified impulses from the photo-cell to step forward an automatic telephone switch: suitable contacts on the switch start an electrically controlled stop-watch, and stop the watch after the meter under test has made the desired number of revolutions. Thus the time occupied by the given number of revolutions is automatically ascertained. The first form of the apparatus had the disadvantage that it was necessary to open the meter and attach a small mirror to its spindle: the method was thus applicable only to type tests, since it would not be permissible to interfere in this way with meters received for normal tests. Mr. Felton has now, however, been able to make the instrument respond to the difference in illumination which results when the black or red spot on the meter disc enters the beam of the lamp: it is thus possible to use the automatic timer without disturbing the meter in any way. The apparatus is still under development, since it is essential that the factor of safety should be high enough to allow for variations in the reflecting power of meter discs and of the spots marked on them, but at the moment its performance appears very promising.

Mr. H. P. Bramwell: As regards the question of dial testing versus timing on held loads, the former method is very slow if much adjustment is necessary, and the latter necessitates the employment of a reliable junior for holding on. Where mixed batches of meters of different makes are to be tested, the meters must be dealt with individually, and stop-watch timing on held loads is the best method for this purpose. For testing batches of new meters of one make, the most efficient method is to calibrate one meter by stop-watch and standard wattmeter, and, using it as a standard, to adjust the others to it by revolution testing. An all-night run on starting current is desirable, and if suitable protection is provided it is not unduly hazardous. A dial test is necessary to check the dial gearing. Turning to the subject of acceptance tests, the programme carried out by the author is undoubtedly thorough, and now that meters are designed to run indefinitely on varying degrees of overload it is very necessary in assessing the relative merits of different meters to know the effect of overload conditions on the meter curve. It is found that 200 per cent full load on a meter will affect the accuracy at half load to the extent of 1 to 2 per cent, and at higher overloads the effect is more marked. Fortunately this effect is not permanent, and disappears as the meter cools down.

Mr. W. L. V. de Palo: I should like to refer to a very satisfactory disc timing method which is in use in Italy. It is a stroboscopic method, and employs a calibrated meter with a metal disc perforated by a definite number

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* *Journal of Scientific Instruments*, 1933, vol. 10, p. 369.

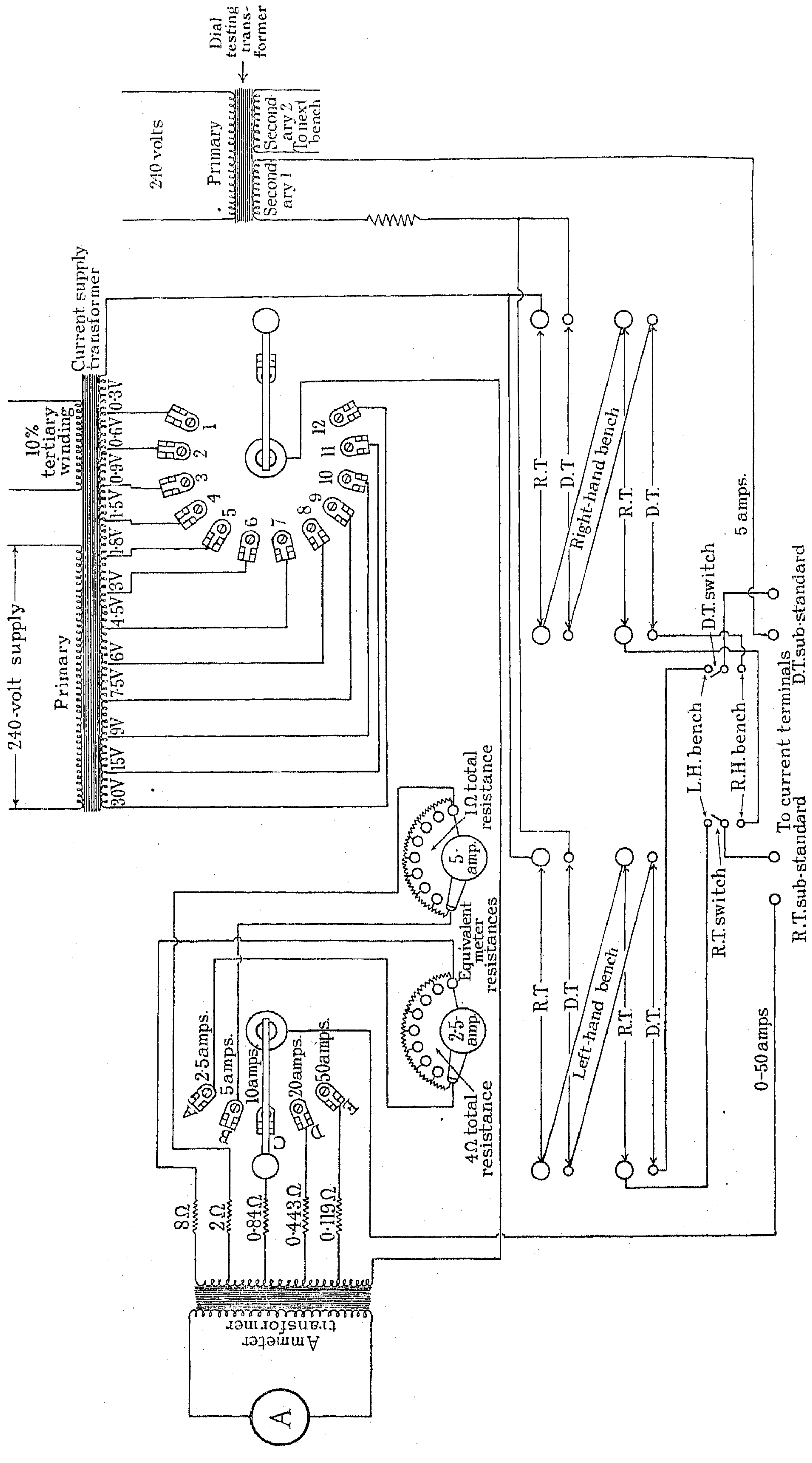

FIG. B.—**Current-supply diagram for single-phase benches.**
R.T. = rate testing. D.T. = dial testing.

of holes, 100 being the number most used. Vertically underneath this is put the meter to be tested, which has an equal number of spots on its disc. A light shines through the aluminium perforated disc on to the lower disc. Both meters are set running, the potential coils being connected in parallel and the series coils in series on the same load. The method enables the operator to calibrate the meter in 10 or 15 minutes. It is much quicker than the stop-watch method, because it enables calibrating to be done at the same time as testing. It would be a great advantage if meter manufacturers would supply a calibrating meter with every batch, thereby greatly simplifying the task of the meter testers.

Mr. A. E. Quenzer: In Section (2) the author refers to the precision current transformer; as the results obtained with this appear to be remarkably good, I should like to know its number of ampere-turns. Towards the end of the same section the author states that in this test he has encountered an instrument error no greater than 0·34 per cent, and at the end of Section (3) he says " it is difficult to tie down differences of the order of 0·2 per cent." In Fig. 15, however, he differentiates between 0·99 and 1 per cent. I should like to know whether the author claims that the second place of decimals has any real significance. Perhaps he would also enlighten us with regard to his ultimate standards. No mention is made of a potentiometer, and I do not know whether he uses one. Fig. 14 shows a difference of 2 per cent in the power-factor tests for maker B. Has the author any explanation to offer for this?

Mr. F. Byrne: I support the author's advocacy of the desirability of testing polyphase meters under polyphase load conditions. The greatest efforts should be made to simulate the conditions in which the meter has to work, and I regret that the view is being expressed amongst meter engineers that polyphase meters may be tested equally accurately under single-phase load conditions. Such a view is dictated, in my opinion, by questions of expense and expediency rather than by technical considerations. I notice that the author rather disparages the use of rotating machinery, but in another part of the paper he mentions the difficulties met with in what he calls "load holding." In my experience, rotating machinery is a great aid in this practical difficulty associated with meter testing. The natural moment of inertia of the rotating machine tends to damp out any fluctuations due to the voltage of the supply, and the flexibility obtainable from the machine is much better than that which can be derived from phase-shifting devices. The author's equipment is designed to a maximum of 500 amperes; many supply authorities have to test metering equipments which exceed this current rating, however, and I should like to know his views on the advisability of testing meters without current transformers and making the necessary technical allowances. Mr. Buckley mentioned the American practice of testing meters by means of phantom loading equipment. The organization with which I am connected uses this method of testing, but the results obtained are not regarded as the ultimate criterion of the accuracy of the meter. The test is carried out merely to disclose any wide variations in its readings. If such variations were disclosed, the meter would be calibrated under test-room conditions.

Mr. J. L. Ferns (*communicated*): It would have been of great assistance to those taking part in the discussion if the author had given a few more particulars regarding the equipment and the personnel of the testing department with which he is connected. No definite information is given regarding the number of meter benches, wattmeters, watches, or testing assistants employed; whether the test-room space is very limited; or whether standardizing equipment is provided. In the case of single-phase meter testing the actual loads on which such meters are given a routine test are not stated. I am not in favour of the type of 3-phase equipment designed by the author, but without the above data at hand one cannot say definitely that it is not the best solution. I should be glad if he could give some more information on these points. Although the correctness of 3-phase testing is rightly emphasized in the paper, the author is still not fully satisfied, judging by the amount of single-phase testing which he still carries out on polyphase meters. Surely it is sufficient to balance the elements on full load only (at unity and 0·5 lagging power factor) before going on with the polyphase calibration. The final settings of the brake magnets and friction compensators do not affect the balance of the elements, and the final performance figures of each element are best obtained, if desired, after the brake magnets and friction compensators have been set by a polyphase test to obtain the best polyphase-error curve. I cannot understand the author's claim that his polyphase testing embodies special features. The method of single-phase testing with the meter under a polyphase voltage supply has been employed for many years, and the routine described on page 53 seems to me to be only a special form of single-phase testing, as the phantom current load does not appear to be a true 3-phase load. Whilst this is quite in order for a 3-wire 2-element meter, which is naturally an unbalanced-load meter, it would be more interesting to know the author's procedure for testing 4-wire 2-element meters. He seems to have taken quite unnecessary pains to prove that the current loading transformers are satisfactory if correctly used. The theory and practice of current transformers surely contain sufficient information regarding the permissible working limits for such transformers to render superfluous the elaborate tests described in Section (3) of the paper. The provision of a voltmeter (with a red danger mark) on the primary windings of the loading transformers would indicate when the limiting conditions of flux density in the core had been reached. This would prevent a newcomer or an inexperienced tester from unwittingly using the incorrect range. I should like to point out, by the way, that these transformers cannot be used for supplying circuits which do not normally take a sinusoidal current, e.g. the primary of a voltage transformer. A danger point of the polyphase equipment when it is split up into single-phase sections is that the testing power-factor may easily be made 0·5 leading, instead of 0·5 lagging, unless strict precautions are taken. Furthermore, without the phase-shifter working, the testing power-factor is not strictly unity or 0·5 lagging, owing to the natural phase angle of the current loading circuit. The statements regarding the overall errors of the sub-standards on page 45 are rather remarkable in view of the remark, on page 41: " It is not altogether satisfactory to rely on sub-standard instruments for measurements unless they are periodically checked," and the fact that the author does not appear to possess any standardizing equipment. Although it is possible to obtain sub-standard wattmeters whose errors are within ± ¼ per cent at full scale on all ranges and all power factors down to 0·5 when new, it must be realized that these instruments have the usual physical limitations which lead to changes in error after usage. The author does not state whether his wattmeters are of the shielded or the unshielded pattern. In the modern test room the latter type is not permissible. Overloading of the voltage and current coils of wattmeters is employed by many engineers, but this practice is not desirable, as it leads to deterioration of the insulation and change of physical state of the resistances and springs. Full-scale readings can now be obtained by a better method than that of overloading the wattmeter windings. It is not stated in the paper whether the precision current transformers are used for testing ordinary current transformers for ratio and phase-angle errors when received new or after use on circuit. Current transformers occasionally develop faults, and it is not sufficient to give a meter a 5-ampere test in order to check this point. Although the author emphasizes the desirability of permanent wiring, he does not indicate any provision for transferring the outputs of the current transformers under test to the meter bench. Furthermore, heavy-current testing would appear to be rather tedious, as no permanent provision for sub-standard current-transformer range-changing is mentioned in the paper.

Mr. J. B. Lees (*in reply*): Mr. Riordan has overlooked the precepts given in the paper with regard to the advantages derived from calibrating to close limits. At different periods we have carried out tests by the three methods discussed, on batches of 500 meters at a time. The resulting experience is overwhelmingly in favour of the timing method. Even as recently as 12 months ago the proportion of meters found to have errors greater than ± 2 per cent often exceeded 20 per cent. Competition and improvement in design are having their effect, however, and the figure tends to decrease materially.

Mr. Buckley confirms my opinion that site testing is best carried out with a rotating sub-standard meter, even when phantom loading apparatus is used. I do not think it necessary to use phantom loading apparatus on domestic consumers' meters. The special voltage-supply method which he describes was, I believe, a conception of the late Dr. Ferranti. Manufacturers, with their individually fixed terminal dimensions, should find the scheme very helpful, as all one has to do is push the meter on to the spring-loaded studs and hook the top fixing lug. The meter is then ready for test.

I am glad to have the support of Mr. Petch with regard to the tests to be performed on current-transformer-operated meters, and am in complete agreement with him in his suggestion that manufacturers should supply definite test data with regard to voltage transformers. I usually specify that the errors be given on the normal service burden, which makes their transposition less liable to error. The test equipment he describes is a very interesting and original conception. It is refreshing to find something new in test-equipment design. The question of open-circuit voltage is dealt with in my reply to Mr. Ockenden.

In reply to Mr. Hunt's remarks with regard to dial testing, I would draw his attention to Mr. Spilsbury's and Mr. Shotter's contributions to the discussion.

I agree with Mr. Howarth that link switches would be an improvement for changing wattmeter voltage-ranges. The reason they are not provided lies in the wide variety of tests which are carried out on the one test equipment. The figure of £276 given on page 45 refers to test equipment only, and does not include measurement apparatus. I am not surprised that Mr. Howarth takes me to task with regard to the economy of the incorporation of a regulation transformer. I have not the facilities to build my own transformers, except quite small ones. The cost of one set of non-inductive resistances was £11 10s., and I was quoted £16 10s. for a regulation transformer, the material cost of which would probably be not more than £8. With regard to polyphase-meter testing, I agree that the " both elements loaded " tests (*a*) and (*b*), Fig. 15, are not essential. For some makes, however, the results obtained are very close to those of the " both elements loaded " tests (*c*) and (*d*), and are therefore valuable as a guide to what one may expect, before actually making tests (*c*) and (*d*). In addition, tests (*a*) and (*b*) do give the response of the meter to a condition where single-phase loads occur simultaneously on the red/white and blue/white phases.

I am surprised to find that Mr. Ockenden does not agree with my method of increasing the sensitivity of wattmeters. The manufacturer of the type we use indicates that we can go up to 250 volts on the 150-volt range and 450 volts on the 300-volt range. This is really nothing more than quoting limiting current, which is quite common practice on the part of manufacturers of non-deflectional-type wattmeters. The point to watch is whether the accuracy is affected by taking advantage of this overload characteristic. We have tested wattmeters which have been on over-voltage for as long as 3 hours, against a cold wattmeter, and have been unable to detect any change in accuracy. Mr. Ockenden has misinterpreted the test data given on page 45 with reference to the use of the 1-ampere wattmeter. They refer to tests on a 5-ampere 230-volt single-phase meter, as indicated. When the precision transformer is being used the 5-ampere wattmeter is always employed with its field coils connected in parallel, giving minimum volt-ampere burden. The results referred to in the outline of tests on a 5-ampere meter are only obtained in part when using the precision transformers because their ratios are 100/1, 50/1, 25/1, 20/1, 10/1, 4/1, and 2/1. The lack of unanimity with regard to symbols is appalling. I adopted those given in Fig. 6 because they are in common use by transformer designers and have the merit of being more or less self-explanatory. With regard to the factor of excellence given in Tables 1, 2, and 3, I prefer the ratio I_L/I_E. The hysteresis current I_H may be anything but sinusoidal, owing, *inter alia*, to the effect of harmonic eddy e.m.f.'s. The question really is: What percentage of harmonics exist in the exciting current? To make this clearer, let us assume that we have a 20 per cent third harmonic in the exciting current, and that the exciting current is 5 per cent of the primary current. The primary current would contain 1 per cent third harmonic. The effect of hysteresis is very prominently shown in the primary current wave (range E, Fig. 7). I agree that it is difficult to predict the peak value obtained on open-circuiting a current transformer. Although the 1-kVA transformers referred to in the paper are repeatedly open-circuited during the coin-testing of prepayment meters, we have yet to experience a breakdown, either in the transformers or in the apparatus connected to them.

In reply to Mr. Ritter, "zero lag" and "zero lead" are conventional expressions used by meter engineers; they are legitimately interpreted as meaning respectively either 90° lag and 90° lead, or 100 per cent lag and 100 per cent lead. Mr. Ritter is quite correct in his suggestion that a secondary phase-shift occurs as a result of the inductive characteristic of the meter current coils. The measuring-wattmeter field coil is, however, connected in series with the meters, and is thus similarly influenced. From the point of view of power factor this phase-shift can be neutralized by the setting of the phase-shifter. A meter does not hold its curve on non-sinusoidal voltage or current, if it has been calibrated with sinusoidal voltage and current. The results given in Fig. 13 illustrate this point. The inductive-load adjustment of any meter effects, in general, a phase-shift of the effective voltage flux only, and it is not possible to control materially the shape of the inductive load curve by adjustment.

I am interested to learn from Mr. Shotter that he has overcome the disabilities of secondary regulation. His single-phase equipment lay-out is very interesting, but would appear to be limited to a maximum loading of 50 amperes. It is on heavy currents that the secondary regulation difficulty becomes acute. It would appear that his experience of carbon rheostats has been happier than mine. We have recently carried out some experiments on meters fitted with brass, aluminium, and "nomag" covers, and have been unable to detect any difference between the calibration obtained with the covers on and that with the covers off.

I am very glad to have the support of Mr. Spilsbury with regard to the accuracy to be expected by timing on held loads. When dealing with repaired meters, we may have six or eight different makes or types on test at the same time, each with a different constant. It is comparatively simple to deal with this complication by the timing method. The photoelectric apparatus to which he refers is a very valuable contribution to meter testing equipment, particularly now that it can be operated "reversed" by the reduction of illumination which results from the entry of the spot into the beam of light. I suggest that Mr. Spilsbury should collaborate with manufacturers with a view to producing the best type of "spot," as I feel that there is a field for this automatic timing apparatus in supply undertakers' test rooms.

I am also glad to have Mr. Bramwell's support with reference to timing on held loads. It is interesting to learn that he has experienced the serious change in errors which arises from series heating.

The stroboscopic methods outlined by Mr. de Palo have been used by manufacturers in this country for a number of years. Stroboscopic calibration is unreliable at rotor speeds below 15 r.p.m., even with 100 spots or lines on the periphery of the rotor. This is due to persistence of vision, and inability to detect small differences in angular velocity of the spots and projected images, at low rotor speeds.

In reply to Mr. Quenzer, the precision transformers have 1 500 ampere-turns. The second decimal place in the values given in Fig. 15 has no real significance. It is our practice to log the timing, and the figures given are those calculated. For example, "— 0·33" means that the timing was 60·2, the correct figure being 60·0. Mr. Quenzer's reference to instrument errors is valuable because it raises the question of what I would call "certified accuracy." If during a test a wattmeter is used which is loaded up to a point on the scale where the wattmeter error can permissibly be, say, 0·34 per cent, and the test on the meter shows it to be running 0·2 per cent slower than it should run, assuming the wattmeter to be correct, the meter can only be certified to have an error at the particular load of ± 0·34 per cent minus 0·2 per cent. I cannot give a detailed explanation of the reason for the divergence of the two 0·5 power-factor curves of maker B (Fig. 14) without disclosing the name of the particular maker. The divergence is due to, amongst other things, the improper application of a curve-compensation feature. The designer would appear to have overlooked the effects of series heating. The procedure adopted in standardizing wattmeters is referred to in my reply to Mr. Ferns.

I agree with Mr. Byrne that a battery-operated d.c. motor-driven alternator gives very steady load conditions. A small alternator suffers the disadvantage that its impedance is not inappreciable. Unless the open-circuit impedance of the transformer connected to it is very much higher, voltage distortion will result from the circulation of the exciting current in the alternator windings. We do not use low-tension metering equipments with a current rating exceeding 2 000 amperes. To test an equipment of this size we loop 4 turns through the transformer. The legitimacy of this practice has been dealt with by Mr. Shotter.* The testing of current-transformer-operated meters is referred to in the Introduction, and also in my reply to Mr. Ferns. Although it is not difficult to deduce what should be the correct calibration curve from given transformer errors, it is desirable to remove the necessity for corrections. The disadvantage lies in the possibility of inaccurate deduction.

In reply to Mr. Ferns, data with regard to personnel and auxiliary equipment were not included in the paper because it was considered that they would not be of general interest. The suitability and technical correctness of testing equipment depend on design and method of use. Although current loading transformers with primary resistance regulation have been in use for 25 years or more, it is my experience that their suitability has been a subject of continual debate. I suggest that my tests are necessary to determine the limiting factors, and are more conclusive than a purely mathematical treatment. With regard to polyphase-meter calibration, the element-balancing method of initial adjustment is quite satisfactory if, during the balancing, the voltages on the two elements have the same phase relationship as they would have on circuit. The results of test (*f*), Fig. 15, indicate how incorrect it would be to attempt balancing with the pressure coils excited in parallel. The suggestion of Mr. Ferns that single-phase testing of polyphase meters excited from a polyphase voltage supply has been in use for many years, is contrary to my experience. Even prominent manufacturers have placed reliance on pure single-phase testing until recently. Our 4-wire meters are of the 3-element type, and in testing we use three current loading panels—connected to red/neutral, white/neutral, and blue/neutral. For the final all-elements-loaded test we have three people holding load, but this has not been found a nuisance, probably because we have very few meters of this type. I agree that standardizing apparatus is highly desirable. I have access to two potentiometers, and if wattmeters become suspect they are checked against these, on direct current, with voltage and current standardized simultaneously. It is pointed out in the Introduction that we do not test current transformers in order to ascertain their errors. If a transformer fails, it does not matter very much what information one has with regard to it. The advantage of knowing what the errors of a transformer are arises when one wishes to connect additional apparatus to it, on site. To avoid doing this, we insert an additional transformer if permanent measurement is necessary, and use apparatus with a clamp-type core for snap tests. We have no current transformers which are not more or less readily removable from circuit. If we were faced with transformers embedded in compound, or similarly inaccessibly placed, it would be necessary to specify that data with regard to errors be supplied, or to install testing equipment. With regard to the final point raised by Mr. Ferns, the precision-transformer ranges can be changed in about 10 seconds.

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* *Journal I.E.E.*, 1930, vol. 68, p. 873.

DISCUSSION ON

"THE MEASUREMENT OF IMPEDANCE."*

Mr. A. T. Starr (*communicated*): The method devised by the author is very ingenious and gives a highly satisfactory accuracy. I cannot, however, understand what he means when he says that my work on the error caused by the wave-form involves a difficulty in defining impedance to a non-sinusoidal current. My discussion was meant to show how the measurement of the impedance to a sine-wave current of a certain frequency was affected by the presence of harmonics in the supply wave, so that one could say that a required accuracy would be obtained if the harmonic content were below some calculable percentage. Further, I have published (*Wireless Engineer*, 1933, vol. 10, p. 609) a note showing how the resistances may be replaced by capacitances. This modification can be applied to the method of Mr. Astbury, so that if r, R_P, R_1, R_2, and R_3, be replaced by C, C_P, C_1, C_2, and C_3 respectively, the formulæ (4) to (8) become

$$Z = \left(\frac{C_1}{C_2}\right)\frac{1}{\omega C}$$

$$R = \left(\frac{C_1}{C}\right)\frac{1}{\omega C_P}\sin\theta$$

$$X = \left(\frac{C_1}{C}\right)\frac{1}{\omega C_P}\cos\theta - \frac{1}{\omega C}$$

$$\sin\tfrac{1}{2}\theta = C_1/(2C_3)$$

and

$$\sin\phi = \tfrac{1}{2}\left[\frac{C_1}{C_2} + \frac{C_2}{C_1} - \frac{C_1C_2}{C_P^2}\right]$$

It is, of course, necessary that the capacitance potential-divider, C_P, keep the constant value C_P. In this method the sign of ϕ is given.

Mr. N. F. Astbury (*in reply*): It is quite clear that Mr. Starr's work does not involve any difficulty in defining impedance to a non-sinusoidal current. My point was that a discussion of the application of the method described to any but sinusoidal currents would be unnecessary and, in fact, useless. In actual practice one proceeds to eliminate as far as possible all harmonics from the supply wave, and from my point of view Mr. Starr's analysis is valuable as showing how far such elimination need be carried out. His modification giving the sign of ϕ is interesting, although, as he himself has pointed out, the appearance of a frequency term explicitly in the equations is a minor disadvantage. The necessity for a capacitance potential-divider seems to be the main objection to this scheme.

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* Paper by Mr. N. F. Astbury (see vol. 74, p. 445).

A VELOCITY-MODULATION TELEVISION SYSTEM.

By L. H. BEDFORD, M.A., and O. S. PUCKLE, Associate Member.

(*Paper first received* 25*th November, and in revised form* 18*th December*, 1933; *read before the* WIRELESS SECTION 7*th February*, 1934.)

SUMMARY.

The paper describes a complete television system operating on the velocity-modulation principle. The theory, advantages, and limitations, of the principle are discussed, and it is shown how these limitations are overcome by the use of a further principle, that of intensification.

The practical development of the system is described in detail, particular attention being given to the transmitting end, where the most fundamental problems are encountered. The results obtained to date (with single-channel wire transmission) are specified.

The complete system is shown to be characterized by the following features:—

(*a*) Absence of synchronizing problem in the line-scanning direction.
(*b*) Simple solution of synchronizing problem in the picture-traversing direction, including automatic framing.
(*c*) Greatly relaxed modulation requirements on the receiving oscillograph.
(*d*) Increased picture-brightness for a given receiving oscillograph as compared with the intensity-modulation system.
(*e*) Favourable concentration of detail in the light portions of the picture.
(*f*) Nearly constant percentage modulation of radio transmitter.

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(1) INTRODUCTION.

The conception of the velocity-modulation principle dates back, as far as it has been possible to trace it, to Boris Rosing,* who described it in 1911. Since that date the principle appears to have fallen into oblivion, and to have been next considered by Thun,† who gave it the name *Liniensteuerung*. The first practical realization of the principle was achieved by von Ardenne‡ in 1931. The present authors were first led to consider velocity-modulation television in December, 1931. At that time they were in ignorance of the earlier publications, and had been led to the principle in a search for a means of circumventing the difficulty of satisfactorily modulating the intensity of the cathode ray. It was, however, the other advantages of the principle, which became apparent on closer consideration, and which in fact had been clearly pointed out by Thun,§ which led to the decision to proceed with the development of a complete television system on a velocity-modulation basis, a development which was actually commenced in August, 1932.

(2) THE VELOCITY-MODULATION PRINCIPLE.

The basic idea underlying the velocity-modulation principle is to obtain light-intensity variations in the received picture by varying not the instantaneous intensity of the scanning spot but its instantaneous scanning velocity, i.e. its speed of traverse over the screen, the actual light intensity of the scanning spot remaining constant. That a true impression of light and dark can be produced in this manner depends upon the phenomenon of persistence of vision. If a light-spot of constant intensity describes a repeating oscillogram, in which the instantaneous traversing speed varies from point to point, the eye will appreciate this state of affairs as such only if the movement is sufficiently slow. If the movement is so rapid that the oscillogram is completed in a period within the persistence of vision, the eye renders a totally different impression, namely that of a stationary oscillogram with variations of brightness along its length. The brightness which the eye associates with an element ds of the oscillogram is that obtained by averaging over a period of time the instantaneous flashes of light which occur as the spot passes through the element. Thus, if the actual intensity of the light-spot is constant, the apparent brightness of the element ds is proportional simply to the time taken by the spot to traverse the element; hence the apparent brightness is inversely proportional to the local instantaneous scanning velocity.

This principle, then, presents the possibility of obtaining light and dark in a received picture without actual modulation of the spot or ray intensity, and it is therefore ideally suited to television reception by means of the conventional cathode-ray oscillograph. Moreover, the cathode-ray oscillograph is practically the only instrument which has sufficient freedom from inertia to reproduce successfully the extremely abrupt changes of velocity* which are called for.

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* See Bibliography, (1). † *Ibid.*, (2). ‡ *Ibid.*, (3). § *Ibid.*, (4).

Consideration shows that it is fundamentally impossible to realize a velocity-modulated received picture from a uniformly scanned object; the scanning at the transmitter must also be velocity-modulated. It follows that the scanning element at the transmitter must also be a cathode ray, which means that, if a process analogous to beam scanning is to be employed at the transmitter, a cathode-ray oscillograph must serve as a source of light. This means that the picture subject-matter will, on grounds of scanning-light economy, be restricted to film material, at least so long as anything comparable with the ordinary low-voltage oscillograph is employed as scanner. In the opinion of the authors, this restriction does not constitute a drawback to the system, as the same restriction is forced upon a television service of any sort from quite other considerations; but it is of technical interest to point out that direct subject transmission is not considered to be outside the bounds of possibility. The present paper is, however, exclusively concerned with the problem of transmitting from film subject-matter, a low-voltage oscillograph serving as scanner.

In essence, then, the immediate problem becomes this: To make the spot of an oscillograph illuminate a cinema film point by point (through a lens), the light transmitted through the film falling on to a photo-cell, and to cause the output from the photo-cell to react back on the scanning oscillograph in such a manner as to control the instantaneous scanning speed. In the case of transmission from a positive picture, increased light on the photo-cell must bring about a decrease of scanning velocity. The path of the spot must, so to speak, be mapped out beforehand into a suitable line *raster*,† which is of such a size and shape as to allow the real image of the spot to explore the whole of one picture; and the photo-cell output must determine only the instantaneous speed of the scanning spot and not its position or intensity. It then comes about that a copy of the picture appears on the screen of the transmitting tube itself; for wherever the real image of the spot falls on an opaque portion of the film the spot itself is speeded up and so gives the appearance of darkness on the transmitter.

The appearance of the picture on the transmitter is a feature of fundamental importance; for since this picture has come about solely by means of the voltages applied to the deflector plates of the oscillograph, the same picture will result on any similar oscillograph to which these voltages are faithfully transmitted.‡ The transmission problem is reduced, in fact, to that of tying the X and Y plates of the receiving oscillograph in parallel with the corresponding plates of the transmitter. If this is done, the question of synchronization does not arise; the synchronism of the system is, in fact, *implicit*. This feature is one of the most important advantages offered by the principle.

The tying together of the X and Y plates of the receiver and transmitter requires, however, fundamentally two communication channels. Von Ardenne* has attempted to transmit these two channels of intelligence, namely the line and picture deflector voltages, over a single physical channel, by making use of a frequency discrimination between them. The solution adopted by the authors differs fundamentally from this, and depends on converting the intelligence to a single channel by sacrificing the feature of implicit synchronism in the picture-traversing direction, whilst retaining it in the line-scanning direction. This state of affairs may be expressed by saying that the synchronism is implicit in the line-scanning direction and explicit in the picture-traversing direction. The picture synchronism, though explicit, is made absolutely solid by means of a signal impressed on the line scanning, so that in effect the system still operates as though the synchronism were wholly implicit.

The principle, as so far described, is seen to offer two advantages: (*a*) Absence of synchronizing problem, at least in the line-scanning direction. (*b*) Absence of intensity modulation of the cathode ray. In addition to these there are two other features to be noted in comparison with the intensity-modulation principle: (*c*) Increased picture brightness for a given receiving oscillograph. (*d*) Concentration of detail in the light portions of the picture.

The last two features, which have been particularly stressed by Thun,† result from the fact that the scanning is relatively slow in the lighter portions of the picture; both the light and the scanning time which are not wanted in the dark places are made use of in the lighter portions.

(3) THE INTENSIFICATION PRINCIPLE.

The last of the above features shows as an advantage only so long as the contrast ratio of the picture is kept low; but as soon as a high contrast-ratio is attempted, the sacrifice of detail in the dark places in favour of the light becomes objectionable, since the detail in the dark is inadequate; further, as is shown later on [see (4·146)], it becomes impossible to obtain a satisfactory transition, more particularly from dark to light, without the use of an unduly widened frequency-band. There are, in addition, very serious practical difficulties in the way of obtaining faithful tone reproduction by pure velocity-modulation [see (4·31)]. The authors were therefore led to consider the possibility of transmitting a velocity-modulated picture at low contrast-level, and superposing intensity modulation upon it at the receiving end. This system proves to be a remarkably advantageous combination of the two principles, since both kinds of modulation work at their best only when called upon to operate over a relatively restricted range. Indeed the intensity-modulation requirements are so far relaxed by the presence of velocity modulation that the ordinary type of gas-focused oscillograph tube, which shows very poor modulation characteristics, is reasonably satisfactory.

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* See Bibliography, (3).

† This word, imported from the German, is used to mean a scanning field or grating.

‡ See Bibliography, (5).

* See Bibliography, (3).

† *Ibid.*, (4).

It might perhaps be supposed that the lowering of the velocity-modulation contrast-level would seriously reduce the advantage of increased picture brightness which is such a valuable characteristic of the pure velocity-modulation principle. This supposition is not realized, the advantage of increased picture brightness being retained almost intact. For, as regards conservation of scanning time, the extremely high scanning velocities which contribute the black picture portions in a pure velocity-modulation picture conserve very little more scanning time for the light picture portions than do the only moderately high scanning velocities characteristic of the intensification system. As regards spot brightness, the spot is at its full brightness in the light portions of the picture, and, since the spot is dimmed only in the dark places, the intensification process involves only the abstraction of light from the places where its presence is detrimental.

In practice the comparison of intensified and unintensified pictures is very emphatically in favour of the former. It is, in fact, the opinion of the authors that only with the addition of intensification does the velocity-modulation principle become a practical proposition.

(4) DEVELOPMENT OF THE SYSTEM.

The development falls into the following three main categories, which, however, cannot be entirely separated:—

The television transmitter [see (4·1) below], that is to say the apparatus for providing a satisfactory picture on the transmitting oscillograph.

The transmission link [see (4·2) below]. This includes all of the apparatus joining up the television transmitter and television receiver, namely, the input to the radio transmitter, the radio transmitter itself, the ether channel, and the radio receiver. For experimental purposes the physical transmission link has been a single wire-line. The complete link for the case of radio transmission will be discussed only in general terms in the present paper.

The television receiver [see (4·3) below], that is to say the apparatus for reproducing the picture which is on the transmitter tube, when provided with a single-channel signal from a suitable part of the transmitting circuit, and also apparatus for intensifying the received velocity-modulated picture.

Of the above items, the one which is most fundamental and which presents the most outstanding difficulty is the first; it has indeed absorbed more than 75 per cent of the development effort, and inevitably occupies a somewhat similar proportion of the present paper.

(4·1) THE TRANSMITTER.

(4·11) *Preliminary Calculations.*

It was arbitrarily decided to aim at a picture frequency of 25 cycles per sec., with a detail corresponding to 120×160 ($= 19\,200$) picture points. This mode of expression refers to standard cinema picture-shape (3×4), with 120-line horizontal scanning or 160-line vertical scanning. According to the usual calculation, this calls for a frequency band of ($19\,200 \times 25 \times \frac{1}{2}$) cycles per sec., or 240 kilocycles per sec. (The authors do not regard the basis of this calculation as entirely satisfactory, but consider that it gives at least the minimum frequency-band required in the case of intensity modulation, and that it provides a rough estimate in the present case.)

Taking 0·5 mm as the diameter of the scanning spot, the smallest allowable size for the picture on the transmitter is then $6 \cdot 0 \times 8 \cdot 0$ cm, whilst the picture should preferably be larger in order to avoid the necessity of considering the "aperture" effect, or finite size of the scanning spot.

The amount of light (in lumens) falling on the photo-cell is easily shown to be

$$\frac{1}{16}F\frac{1}{N^2}\cdot\frac{1}{(1+M)^2}\eta_1\eta_2$$

where F is the total light flux of the scanning spot (lumens), N is the "*f* number" of the lens, M is the linear magnification ratio of the screen picture to film picture, η_1 is the transmission coefficient of the film at any particular picture point, and η_2 is the transmission coefficient of the lens.

From this it is seen that the useful light diminishes very rapidly with the magnification ratio; it was therefore proposed to work with the above-mentioned minimum size of screen picture, giving a magnification ratio of 3·6 : 1 approximately.

The requirement as to signal strength from the photo-cell is simply that the signal voltage across the photo-cell output resistance should be large compared with the total noise-voltage equivalently expressed. Previous experience[*] had shown that this noise might be expected to be principally constituted by the thermal-agitation noise (Johnson noise[†]) in the photo-cell anode resistance. Taking this, for reasons which appear later, as 1 megohm, we find that the r.m.s. noise voltage corresponding to a frequency band of 240 kilocycles per sec. is 62 μV. In this calculation the capacitance across the 1-megohm photo-cell anode resistance is neglected, because the amplifier has to be so compensated as to make this capacitance appear zero over the frequency band concerned. One may therefore specify provisionally that the photo-cell voltage corresponding to full film-transparency should be of the order of 1 mV, that is to say the photo-cell current should be 1 millimicroampere.

Measurement with hard potassium photo-cells and a calcium-tungstate oscillograph (Cossor Type C) showed that such a current could be obtained with a gun voltage of the order of 2 000 volts and a lens of aperture *f*/1·9. (Unfortunately so easy a solution was not realized in practice on account of the after-glow of the calcium-tungstate screen, which, as is shown later, has the effect of reducing the signal strength more than 8 times. In consequence of this it proved necessary to increase both the gun voltage and the lens aperture, and even to reduce somewhat the magnification ratio.)

The above calculations led to the conclusion that the "size" of the picture on the transmitter would, expressed in terms of deflector voltages, be 380×285, whence it was estimated that a d.c. supply voltage of 500 volts would be required for the time-base circuits.

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[*] See Bibliography, (6).

[†] *Ibid.*, (7).

(4·12) *Basic Transmitting Circuit.*

Fig. 1 shows a purely schematic version of the transmitting circuit (for a stationary picture) by which velocity-modulated scanning, and the appearance of the picture on the transmitter, is brought about.*

The screen-grid valve V_1, condenser C_1, and gas-discharge triode or thyratron V_2, constitute a time-base circuit, the valve V_1 forming the "constant current" charging element, in view of its being operated with the plate voltage well above that of the screen, that is to say in the saturated part of its anode-current/anode-voltage characteristic. The instantaneous charging current is determined from instant to instant by the voltage on the grid of V_1, which voltage is actually the output of the photo-cell amplifier. The bias on the grid of the thyratron V_2 determines, at least nominally, the voltage amplitude of the time-base sweep. The cathode of V_2 is connected to one of the X deflector plates (P_{x_1}) of the oscillograph, the opposite plate (P_{x_2}) being taken to a biasing potentiometer for the purpose of shifting the picture. The arrangement thus constitutes a time base which provides a scanning sweep whose speed is modulated by the instantaneous amount of light falling on the photo-cell, and a rapid fly-back on the occasion of each discharge of the thyratron. This fly-back is so rapid as to be invisible, so that it is not necessary to quench the spot on the fly-back in order to obtain a correct picture.

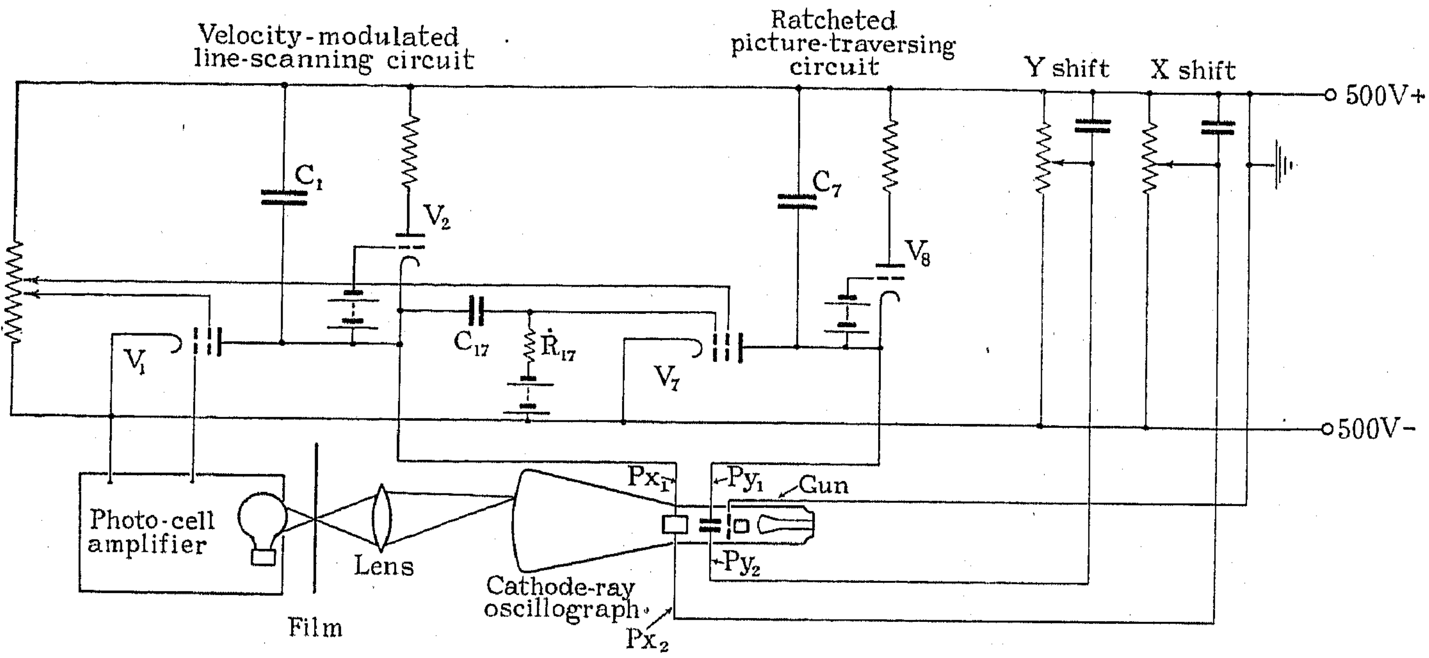

FIG. 1.

The type of scanning described above has been termed "constant-voltage scanning," in contradistinction to an alternative arrangement which was first contemplated and used,† called "constant-time scanning." In the former case the scanning lines are allowed to take their own time, which will vary from line to line according to the amount of light or dark encountered by the scanning spot, the lines being all of the same "voltage length." In the latter case the lines are all caused to take the same time; this is done by providing a locking arrangement which holds the spot at a point beyond the boundary of the picture until the thyratron V_2 is fired by a timed pulse on its grid. This latter arrangement has been found uneconomical in scanning time, and has been abandoned.

Coming now to the picture-traversing circuit, the screen-grid valve V_7, condenser C_7, and thyratron V_8, constitute the traversing time-base. It will be appreciated that, unless constant-time scanning is used in the line-scanning circuit, it is not satisfactory for the traversing time-base sweep to be uniform; for, if this were the case, the scanning lines would not be straight, and the pitch would be opened out in the bright portions of the picture. Two alternatives present themselves: either (*a*) the traversing velocity may be modulated along with that of the line scanning, in such a way that the two velocities hold a constant ratio; or (*b*) the scanning line may be moved on in a stepwise manner between consecutive lines, the magnitude of the step being fixed and independent of the time taken by the line. Either of these arrangements has the effect of reducing the 2-dimensional scanning raster to a single degree of freedom. The latter alternative, which may be termed a "ratchet" arrangement, is adopted in the present case.

In Fig. 1 the ratcheting effect is obtained thus. The condenser C_{17} and resistance R_{17} form a species of differentiating circuit, and the high rate of change of voltage corresponding to the discharge of V_2 causes a pulse of voltage to appear across the resistance R_{17}; the bias on the grid of V_7 is such as to cause the anode current to be completely cut off except on the occasion of the pulse. As all the pulses are similar, and as V_7 is operated on the saturated part of its anode-current/anode-voltage characteristic, it follows that equal increments of charge are fed into condenser C_7 at every line fly-back, and so the requisite ratchet motion is obtained.

In the simplified schematic arrangement here discussed, the picture traverse is, like the line scanning, on a constant-voltage basis, the picture discharge occurring, in its own time, whenever the voltage across the condenser C_7 reaches a certain value, preset by the grid-bias voltage on the thyratron V_8. In practice this arrangement is departed from, and the picture-traversing is made to proceed on a constant-time basis, in a manner which will be made clear in the description of the complete transmitter.

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* See Bibliography, (5).

† *Ibid.*, (5).

It is now convenient to consider the wave-form of the scanning deflector voltage which characterizes the above

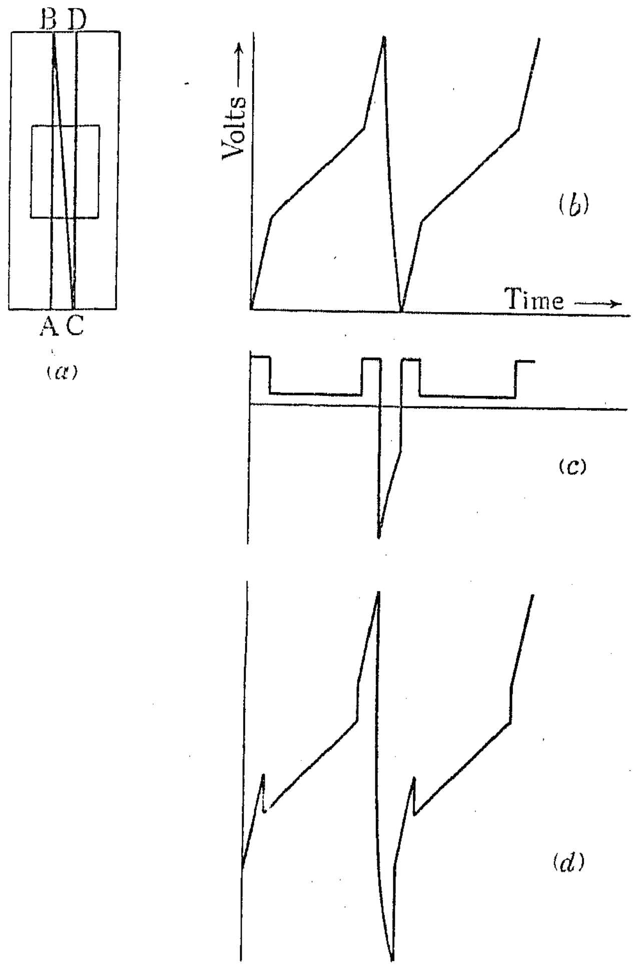

Fig. 2.

arrangement; for it is this voltage which has to be conveyed, directly or indirectly, to the receiving oscillograph in order to reproduce the velocity-modulated picture. Fig. 2(*a*) shows an extremely simple picture to be transmitted, consisting of a white rectangle in the middle of a dark field. AB and CD represent a pair of consecutive scanning lines, the faint line BC, which is not necessarily straight, representing the fly-back. In Fig. 2(*b*) the corresponding deflector-plate voltage (on P_{X1} of the transmitter) is plotted against time, whilst underneath this curve its time derivative is plotted to the same scale (Fig. 2*c*). The voltage corresponding to the scanning line AB rises steeply at first whilst the spot scans rapidly over the dark field, then more slowly as the spot moves over the white rectangle, and again steeply as the spot moves over the dark field; then follows a rapid fall of voltage corresponding to the line fly-back; in this portion of the curve the transparency variations of the film produce no effect, as the discharge valve takes control. The derived curve (Fig. 2*c*) is very much like the curve which would correspond to the transmission of the same picture in the intensity-modulation manner, except that the time scale is stretched in the light and compressed in the dark portions of the picture.

(4·13) *Practical Transmitting Circuit.*

The practical transmitting circuit shown in Fig. 3 differs from that of Fig. 1 in many points of both detail and principle; of these differences the following may be listed in advance. (1) Addition of timer circuit, providing pulses of picture frequency (25 cycles per sec.). (2) Provision of facilities ("chasing circuit") for transmission of moving pictures from a uniformly running film. (3) Substitution of thyratron V_2 of Fig. 1 by a pair of hard valves, V_2 and V_3 (Fig. 3). (4) Improved ratchet mechanism involving the ratchet driver valve V_4 (Fig. 3). (5) Picture-synchronizing signal impressed via "locking valve V_5" on scanning circuit in the form of a temporary cessation of scanning at the end of the last line. (6) Inclusion of resistances R and R′ in series with the condenser C_1. (7) Provision of output valve V_6 with condenser-resistance potentiometer input and 500-ohm output for transmission of signal to line or radio transmitter.

The last three features are concerned more strictly with the transmission-link and receiver aspects of the case, and, except for item (5), which plays a fundamental role in the transmitting circuit, can be left out of consideration here.

The valve V_1, which belongs electrically to the scanning panel, is located physically in the photo-cell amplifier, in order to save wiring capacitance on the grid side.

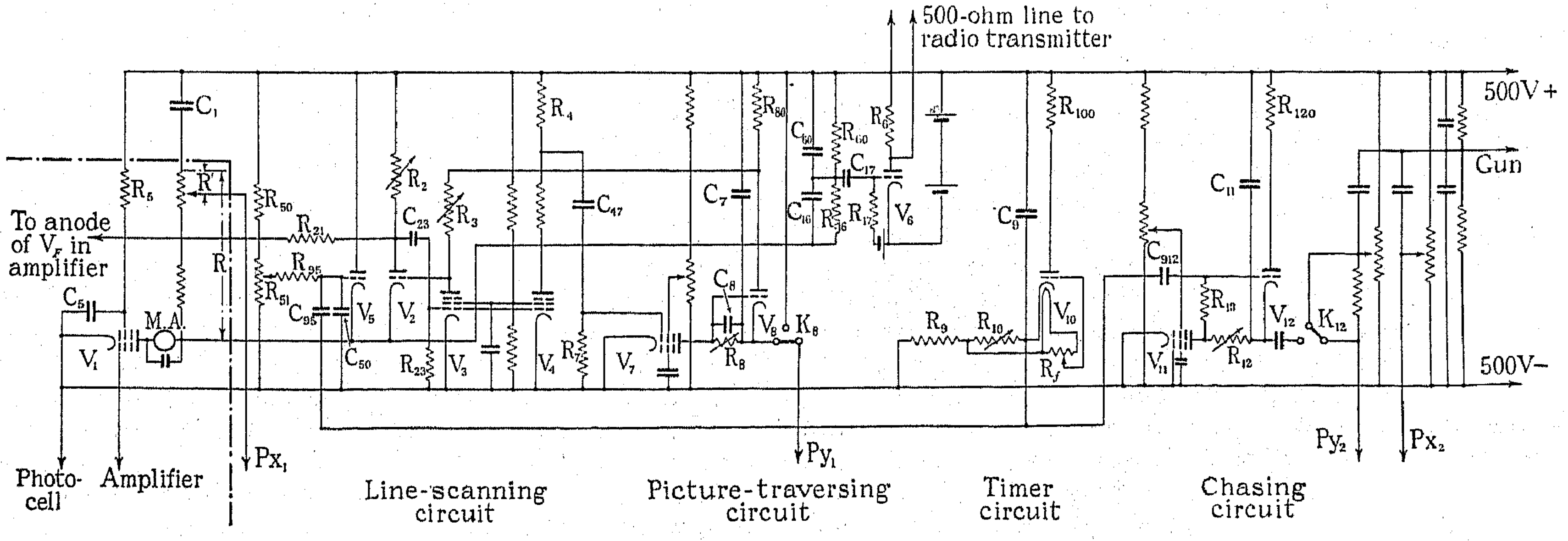

Fig. 3.—Scanning panel.

Whilst V_1 has to show fundamentally the saturated characteristic of a screen-grid valve, it is in practice found necessary to make it a screened pentode; the essential reason for this will appear later. The particular pentodes used were found incidentally to show a better saturated characteristic than the tetrodes, and pentodes were therefore adopted for all the "constant-current charging valves," namely V_1, V_7, and V_{11}.

The substitution of the hard valves V_2 and V_3 for the thyratron V_2 of Fig. 1 was an extremely important step.* The necessity for it arises from the fact that when the scanning lines are allowed to take their own time, this time can vary over a relatively wide range. With such varying frequencies, it was not possible to make a thyratron which would fire at a constant voltage amplitude; indeed at the higher frequencies corresponding to a succession of dark scanning lines the behaviour of the thyratrons was found to be completely erratic.

In the case of the hard-valve circuit the operation is as follows. During the charging of the condenser C_1, the valve V_2 takes no anode current owing to its being biased beyond cut-off by the drop in the resistance R_3 in the plate circuit of V_3. As the charging continues, the voltage across V_2 rises until a point is reached where anode current commences to flow; this causes a voltage drop over the resistance R_2, which is fed through condenser C_{23} on to the grid of the valve V_3. This reduces the current in R_3; hence the grid voltage of V_2 rises, the anode current increases, and the action is cumulative. At the end of the discharge the current in R_2 drops, the cumulative action is reversed, and the circuit resets itself for the next charging stroke.

This circuit has been found to be entirely free of the defect in the thyratron circuit, and has, in the opinion of the authors, proved superior to it in every way.

The anode of the valve V_3 makes a large excursion in voltage in the positive direction on the occasion of every fly-back. It is therefore tempting to use this voltage for the ratchet drive on the grid of V_7, instead of using the differentiating circuit of Fig. 1. As, however, the rise of the anode voltage of V_3 is checked by the grid current of V_2 during the discharge, it is preferable to use a separate ratchet driver valve V_4, whose grid and screen are paralleled to those of V_3, but whose anode is free of the load of the grid of V_2. This anode is taken to positive H.T. via a resistance R_4, and drives the grid of the ratchet valve V_7 via the condenser C_{47}; the resistance R_7 biases back the grid until it takes only a small excursion into grid current on each line fly-back; this bias is sufficient to hold the anode current of V_7 completely cut off during the actual scanning lines.

The neon thyratron V_8, which serves as discharger for the ratcheted picture traverse, is biased by the voltage drop over resistance R_8 in the anode circuit of V_7. This anode current being pulsatory, it is necessary to provide a condenser C_8 to hold up the bias between pulses. Herein lies the essence of the picture-synchronizing process, in that the time-constant C_8R_8 is made only long enough to hold up for one scanning line of maximum length, and any delay impressed on the scanning longer than this period causes the thyratron V_8 to discharge.

Such a delay is impressed every $\frac{1}{25}$ sec. by means of the timer circuit. This consists of the resistances R_9, R_{10}, condenser C_9, and thyratron V_{10}, which constitute a simple (non-linear) time base. The circuit is adjusted to pulse at 25 cycles per sec., being synchronized on to the 50-cycle mains by means of the potentiometer R_f across its heater.

As a shunt path to the discharge valve V_2 there is placed a similar valve V_5, which acts as a "locker." The grid of this valve is biased by the potentiometer R_{51} to a potential lower than that of the grid of V_2, so that V_5 passes no anode current within the excursion of cathode voltage corresponding to the picture lines. The timer pulse is fed on to the grid of V_5 via the condenser potentiometer $C_{95}C_{50}$, and is such as to make the grid of V_5 more positive than that of V_2. In this condition V_5 robs V_2 of anode current, and the scanning is held up. After the timer pulse, the grid voltage of V_5 falls back to its more negative value on account of the collapse of the time-constant circuit $C_{50}R_{95}$, and only when the grid voltage of V_5 falls below that of V_2 does the line discharge occur. The time-interval allowed for the scanning stop is adjusted by the setting of the potentiometer R_{51}, and is arranged to be rather longer than the longest possible line time. The time-constant circuit C_8R_8 is adjusted to collapse far enough within this period to ensure discharge of V_8.

What now are the advantages of this extraordinarily indirect method of timing the picture-traverse discharge? Primarily the advantage is at the receiver. Since the latter receives its intelligence in the form of the line-scanning voltage, it is necessary that this voltage should carry the picture-synchronizing signal. There is also the subsidiary advantage that this particular form of signal places the picture fly-back line at the boundary of the picture, where it can be masked off.

The circuit so far described is all that is necessary for the handling of a stationary picture. For dealing with moving pictures it is naturally desired to scan a uniformly running film rather than the intermittently moving film of cinematograph practice, since the latter would involve a loss of scanning time of the order of 25 per cent. To provide this facility, a fourth time-base circuit, termed the "chasing circuit," is added. The film is run uniformly through the gate at exactly 25 frames per sec., this being ensured by the use of a synchronous driving motor; the film is "phased" by means of a take-up roller so that the picture-change point coincides with the timer pulse, the latter being synchronized off the same mains as the driving motor. The chasing circuit superposes a linear saw-tooth motion on to the whole of the scanning, of such direction and magnitude as exactly to neutralize the motion of the film. The fly-back of this motion, which constitutes the frame change, is synchronized from the timer discharge by means of the condenser C_{912}. (In a previous arrangement the functions of timing and chasing were combined in a single time-base circuit.)

This particular form of chasing compares favourably with the procedure, known in intensity-modulation systems, of collapsing the scanning to a single line and allowing the film motion to provide the traverse, since by means of the new method it becomes unnecessary to transmit the blank bars between successive frames, which in modern film practice represent some 16 per cent of the gross picture. Not only this, but if the scanning is set to cover a net picture, whilst the chasing is set to cover a gross picture, the scanning field cannot collapse to a single line, but only to a narrow rectangle; in this way screen burning or fatigue, which might occur with the excessively high bombardment intensity corresponding to a single-line scanning field, is avoided.

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* See Bibliography, (8).

The keys K_8 and K_{12} are used in conjunction with the chasing in the following way. To set up the chasing, K_8 is thrown up, which suppresses the traversing motion, and K_{12} is thrown down. The chasing velocity is then adjusted, by means of the screen voltage of V_{11}, until exactly one gross picture is covered. The two keys are then reversed and the traversing pitch is adjusted by means of the screen voltage of V_7 until one net picture is covered. Finally, K_{12} is again thrown down when the film is set in motion.

When the chasing is put on to the transmitter tube the picture naturally becomes unintelligible; therefore a separate tube, termed the monitor tube, is paralleled on to the P_{X1} and P_{Y1} plates of the transmitter, but is provided with separate shift potentiometers for its P_{X2} and P_{Y2} plates. The monitor tube therefore receives the line-scanning and picture-traversing motions, but not the chasing motion; it thus provides a properly intelligible picture for both stationary and moving films.

The resistances R_{80}, R_{100}, and R_{120}, are limiting resistances in the thyratron anode circuits, but one of these, R_{80}, performs a second function. The resistance R_3 in the anode of V_3 is taken to H.T. positive via the resistance R_{80}. This ensures that the line discharge cannot take place during the picture discharge.

The resistance R_{21} between the anode of V_2 and that of V_F in the amplifier causes a negative pulse to be applied to the grid of V_1 during the line fly-back. This pulse is sufficient to suppress the anode current of V_1, and so ensure a constant fly-back time; this is very necessary in order to secure a uniform pitch in the picture traverse.

The feed resistance R_s and "decoupling" condenser C_s for the screen of V_1 constitute an important feature. Since the light portions of the picture are scanned at a lower speed than the dark, it follows that with a constant picture time a generally dark picture will be over-completed and a generally light picture under-completed; that is to say, the height of the picture will continually be varying. The screen feed arrangement to V_1 constitutes what may be called an "automatic monitor" which takes care of this point. As the working screen voltage is only a small fraction of the 500-volt H.T., the conditions amount to feeding the screen of V_1 at constant current; this causes the mean anode current V_1 to hold likewise a substantially constant value, which is the condition required for maintaining a constant picture height.

(4·14) *Photo-Cell Amplifier.*

The design of the photo-cell amplifier, which has proved one of the most difficult problems in the development, has to meet the following requirements. (1) Voltage gain of the order of 5 000 times. (2) Effectively level frequency-characteristic from 25 to 240 000 cycles per sec. (3) A minimum of phase distortion. (4) Minimum phase-delay. (5) Total valve and resistance noise to be a minimum. (6) Low level of microphonic noise. (7) Freedom from instability of all kinds. (8) Freedom from pick-up, e.g. of the scanning voltages. (9) Preferably should run off mains.

The fulfilment of requirements (2), (3), and (4), calls for compensation for the stray capacitance across the photo-cell, and compensation for the stray capacitances across the anode resistances of the amplifying valves, all of these stray capacitances themselves being kept at a minimum. Unfortunately this is not all the compensation necessary; there is further required compensation for the after-glow of the fluorescent material of the scanning oscillograph.

This after-glow effect, whose manifestation was a most serious blow to the development, made itself evident in the following way. It was found that whilst good picture definition could be obtained at low scanning speeds, the definition fell away rapidly as the scanning speed was increased, although the frequency characteristic of the amplifier itself was more than adequate. To explain this effect, the theory of a screen after-glow was proposed hypothetically, and was found to fit the facts. Recently von Ardenne* has obtained very direct evidence of the screen after-glow, and has also made measurements which agree in order but not in detail with those of the authors.

The theory of the screen after-glow and its compensation forms part of a detailed discussion of the amplifier, which will now be given.†

(4·141) *Theory of Screen After-glow.*—The fluorescent light of a material under electron bombardment is generally regarded as being due to the return to normal energy-level of atoms or atomic complexes after excitation to higher energy-levels by the electron bombardment. In these circumstances the response can hardly be absolutely instantaneous, although the after-glow time may be extremely short, e.g. a small fraction of a microsecond. In the absence of a clear picture of the detailed mechanism of fluorescence, one may make the physically probable hypothesis that the light response dF to an infinitely short bombardment by a charge dq at voltage V is given by

$$dF = kdqe^{-\frac{t}{T}}$$

where dF is the instantaneous light flux at time t after the bombardment, k is a constant depending on the gun voltage V, and T is the time-constant of the fluorescent material. What then is the response to a current I (at voltage V) suddenly applied? Reckoning t from the moment of application, clearly this response is given by

$$\begin{aligned} F &= \int_0^t k\,.\,dq\,.\,e^{-\frac{t'}{T}} \\ &= \int_0^t kIe^{-\frac{t'}{T}}dt \\ &= kIT\,[1 - e^{-t/T}] = k'I[1 - e^{-t/T}] \end{aligned}$$

Thus we see that the assumption of an after-glow of the kind specified leads to the conclusion that the response to a suddenly applied bombardment is also not instantaneous.

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* See Bibliography, (9)

† This portion of the paper unfortunately constitutes a digression from the main argument, and Sections (4·141) to (4·15) may well be omitted on a first reading.

Now apply the theory to the case of an infinitely small scanning spot traversing the screen at velocity u. It covers an element ds of its course in a time ds/u; the ray current being I, the element is stimulated to give a light response $kI(ds/u)e^{-t'/T}$, t' being now measured from the time the spot crosses the element ds. The total light being emitted from the screen is given by

$$\int_0^\infty kI\frac{ds}{u}e^{-\frac{t'}{T}}$$

In this integral, the value of t' to be associated with each element ds is the "time ago" at which that element was scanned, the zero of time being taken at the ray point. This integral may be written

$$\int_0^\infty kIe^{-\frac{t'}{T}}dt' = kTI = k'I$$

Next consider the case of an infinitely small scanning spot traversing the screen and throwing an image on to the film with transparency η, and suppose that this changes abruptly from value η_1 to value η_2. The light on the photo-cell at time t after the transition is

$$\begin{aligned}\eta_1\int_t^\infty kI\frac{ds}{u}e^{-\frac{t'}{T}} &+ \eta_2\int_0^t kI\frac{ds}{u}e^{-\frac{t'}{T}}\\ &= \eta_1 kI\int_t^\infty e^{-\frac{t'}{T}}dt' + \eta_2 kI\int_0^t e^{-\frac{t'}{T}}dt'\\ &= kIT\left[\eta_1 e^{-t/T} + \eta_2(1 - e^{-t/T})\right]\\ &= k'I\left[\eta_1 e^{-t/T} + \eta_2(1 - e^{-t/T})\right]\end{aligned}$$

This, however, is an expression of very well-known form; operating on it with $(1 + TD)$, we get

$$k'I\left[\eta_1 e^{-\frac{t}{T}} - \eta_1 e^{-\frac{t}{T}} + \eta_2 - \eta_2 e^{-\frac{t}{T}} + \eta_2 e^{-\frac{t}{T}}\right] = k'I\eta_2$$

This is just what we should get by making T tend to zero in the other expression, that is to say if the after-glow was infinitely short.

It follows that the compensation required for the after-glow is the very simple operator $(1 + TD)$.

The graphical expression of this matter may be seen in Fig. 9. The discontinuous curve (0) represents the transition in the ideal case of no after-glow, the continuous curve (1) the case of a finite after-glow of time-constant T. Operating on the latter with $(1 + TD)$ converts it to the former.

Physically one may regard the after-glow as causing the scanning spot to be not punctiform, but elongated, the brightness dying away from the head in an exponential fashion. The after-glow thus introduces a kind of "aperture" effect in spite of the punctiform section of the ray head; but it is an aperture effect which allows much more simple compensation than a finite length of constant brilliance. Moreover, it is to be noted that the speed of the spot does not come into the question, the argument holding equally for constant-speed or velocity-modulated scanning. The aperture effect proper can hardly be compensated when the scanning velocity is variable.

(4·142) *High-frequency Compensating Circuits.*—The form of operator required for after-glow compensation will be recognized to be identical with that required for compensating the photo-cell circuit, and also for each of the anode circuits of the coupling valves. We therefore require compensations of one mathematical form only, that is to say such as to give the operation $(1 + TD)$ or, in terms of frequency characteristic, $(1 + jpT)$. Circuits for this form of compensation are well known. The authors have used two varieties, shown in Figs. 4 and 5. In Fig. 4, so long as it is permissible to neglect the stray capacitances C' and C_2 and the damping resistance R' (which is put in to prevent the circuit peaking at the resonance frequency of the circuit LC′), and to regard the valve impedance and the resistance R_3 as infinite, the gain of the valve may be written in the form

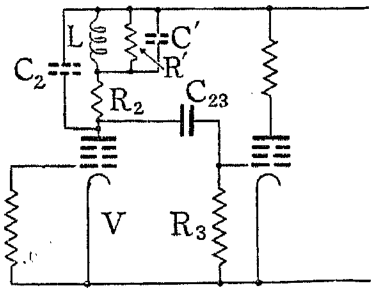

FIG. 4.

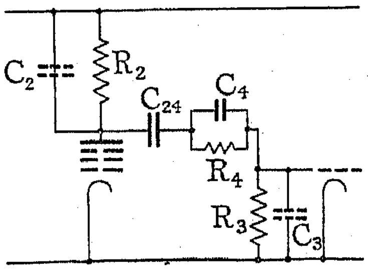

FIG. 5.

$$mR_2\left(1 + jp\frac{L}{R_2}\right)$$

an expression which shows the required type of operating factor. When, however, the stray capacitances and damping resistance are taken into account, the expression for the gain takes the more complicated form

$$mR_2\frac{1 + jp\left(\frac{L}{R_2} + \frac{L}{R'}\right) - p^2LC'}{1 + jp\left(C_2R_2 + \frac{L}{R'}\right) - p^2L\left[C' + C_2\left(1 + \frac{R_2}{R'}\right)\right] - jp^3LC'C_2R_2}$$

This circuit has not been found very suitable for compensating long time-constant effects, such as the photo-cell resistance time-constant (17 microseconds) and the after-glow time-constant (6 microseconds), because the appearance of the higher-order terms necessitates working with very low values of R_2. This means not only low gain, but also that trouble is encountered when it comes to running the amplifier off the mains, because of the finite impedance of the decoupling condensers; further, it is not suitable for providing a continuously variable compensation, since the only conveniently variable quantity is R_2, and alteration to this at the same time varies the gain. The circuit is, however, intrinsically suitable for compensating the individual capacitances in the amplifying stages.

The circuit of Fig. 5* has been found much more convenient for the compensation of the photo-cell circuit and after-glow time-constants. In this circuit R_3 is no longer a high resistance but is of the same order as R_2. The expression for the gain, from the point of view of the grid of the second valve, works out to

$$mR_2\frac{R_3}{R_s}\frac{1+jpT_4}{\left\{1+jp\left(\frac{R_2+R_3}{R_s}T_4+\frac{R_4+R_3}{R_s}T_2+\frac{R_4+R_2}{R_s}T_3\right)-p^2\left[\left(\frac{R_3}{R_s}T_2+\frac{R_2}{R_s}T_3\right)T_4+\frac{R_4}{R_s}T_2T_3\right]\right\}}$$

where $R_s = R_4 + R_2 + R_3$, $T_4 = C_4R_4$,
$T_2 = C_2R_2$, $T_3 = C_3R_3$,

and the capacitance of the coupling condenser C_{24} is taken as infinite.

If the time-constants T_2 and T_3 are neglected, this expression simplifies to

$$mR_2\frac{R_3}{R_s}\frac{1 + jpT_4}{1 + jp\frac{R_2 + R_3}{R_s}T_4}$$

Provided, then, that the fraction $(R_2 + R_3)/R_s$ is kept small, the expression shows the required compensating operator with time-constant T_4. The advantage of this circuit is that the capacitance C_4 can be made the variable quantity, so that the compensation can be varied without simultaneously varying the gain.

There is one other form of compensating arrangement, consisting of a species of feed-back circuit, which was originally used for compensating the photo-cell input capacitance directly.† This is illustrated in Fig. 6, which shows the first three stages of the amplifier as viewed in the alternating-current sense. The voltage from the plate of the second amplifying valve is fed through a very small variable condenser C′ back to the grid of the first valve. If the stray capacitances C_2 and C_3 are neglected, the theory of the circuit becomes very simple; the effective capacitance across R_1 becomes $[C_1 - (\mu_1\mu_2 - 1)C']$, where μ_1 and μ_2 are the voltage gains of the first two stages. Thus the effective capacitance can be reduced to zero or to a negative quantity.

When, however, the stray capacitances are taken into account, the expression for the behaviour of the circuit becomes very much more complicated, and takes the form

$$v_3 = \frac{\mu_1\mu_2 + T_3''D + T_2T_3D^2}{\{1 + (T_1' + T_2 + T_3 - \mu_1\mu_2T_1'')D + (T_2T_3' + T_3'T_1' + T_1'T_2 - T_1''T_3)D^2 + (T_1'T_2T_3' - T_1''T_2T_3')D^3\}}R_1i$$

where

$$T_1' = (C_1 + C')R_1, \quad T_1'' = C'R_1,$$
$$T_2 = C_2R_2, \quad T_3 = C_3R_3,$$
$$T_3' = (C_3 + C')R_3, \quad T_3'' = C'R_3,$$

and i is the photo-cell current.

If all the time-constants except those containing R_1 are neglected, the expression becomes

$$v_3 = \frac{\mu_1\mu_2}{1 + (T_1' - \mu_1\mu_2T_1'')D}R_1i$$
$$= \frac{\mu_1\mu_2}{1 + [(C_1 + C')R_1 - \mu_1\mu_2C_1'R_1]D}R_1i$$
$$= \frac{\mu_1\mu_2}{1 + [C_1 - (\mu_1\mu_2 - 1)C']R_1D}R_1i$$

which agrees with the simple theory given above.

From the more complicated expression it follows that as the effective capacitance across R_1 is reduced by an increase of C', the circuit goes into oscillation at the zero point; the frequency of this oscillation is of the order

$$\frac{1}{2\pi\sqrt{[T_1(T_2 + T_3)]}}$$

Even before the zero capacitance is reached, a selective amplification of frequencies in this region sets in. Hence the circuit cannot be employed to reduce the photo-cell circuit capacitance indefinitely, but it might conceivably be used in conjunction with one of the other compensating circuits in a later stage. It must be pointed out, however, that the circuit suffers from a further drawback, namely that any noise generated in the plate circuit of the first valve becomes exaggerated by reason of its being fed back on to the grid.

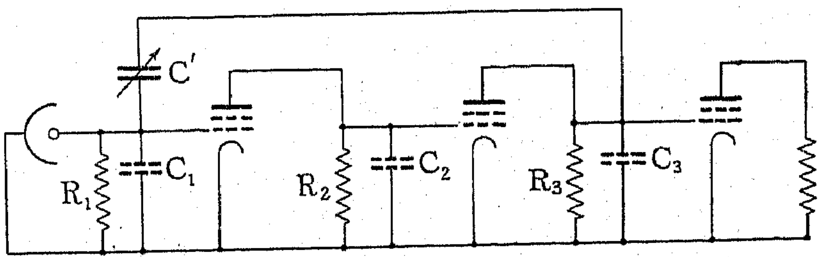

FIG. 6.

(4·143) *Signal/Noise Ratio.*—The consideration of signal/noise ratio is of fundamental importance in the design of the amplifier; in particular, it dominates the choice of the photo-cell anode resistance, which in its turn determines the value of the time-constant of the photo-cell compensating stage.

For the thermal e.m.f. in the photo-cell anode-resistance we take Johnson's formula‡ in the form

$$E = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}f_b^{\frac{1}{2}}$$

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* See Bibliography, (10).

† *Ibid.*, (10) and (11).

‡ *Ibid.*, (7).

where E is the r.m.s. noise voltage in microvolts, θ the absolute temperature, R_1 the anode resistance (ohms), f_b the frequency band (cycles per sec.), and J the Johnson constant (equal to $7 \cdot 4 \times 10^{-6}$ with the above units).

For the e.m.f. corresponding to the small frequency-band f to $f + df$ we have then,

$$dE = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df$$

The corresponding potential difference appearing across R_1 is less than this owing to the loading effect of the shunt (stray) capacitance C_1, and is given by

$$dV = J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{\surd(1 + 4\pi^2f^2C_1^2R_1^2)}$$

The corresponding voltage on the plate of the first amplifying valve is

$$J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{\surd(1 + 4\pi^2f^2C_1^2R_1^2)} \cdot mZ_2$$

where m is the mutual conductance of the valve, and Z_2 the (modulus of the) plate-facing impedance. On the plate of the first valve after the compensating circuit, this voltage appears as $J\theta^{\frac{1}{2}}R_1^{\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}dfmZ_2\mu'$, where μ' is the effective amplification at low frequency between the plate of the first valve and that of the first valve after the compensation.

For the shot noise on the first anode we may assume* an expression

$$V' = KZ_2f_b^{\frac{1}{2}}$$

where K is the appropriate shot constant.

Thus

$$dV' = KZ_2\tfrac{1}{2}f^{-\frac{1}{2}}df$$

This appears on the plate of the first valve after the compensation as

$$KZ_2\tfrac{1}{2}f^{-\frac{1}{2}}df\mu'\surd(1 + 4\pi^2f^2C_1^2R_1^2)$$

The signal voltage at this plate is $R_1imZ_2\mu'$

Hence we find that

$$\frac{\text{Component of Johnson voltage}}{\text{Signal voltage}} = J\theta^{\frac{1}{2}}R_1^{-\frac{1}{2}}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{i}$$

and $\dfrac{\text{Component of shot voltage}}{\text{Signal voltage}}$

$$= KR_1^{-1}\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{mi}\surd(1 + 4\pi^2f^2C_1^2R_1^2)$$

$$= K\tfrac{1}{2}f^{-\frac{1}{2}}df\frac{1}{mi}\sqrt{\left(\frac{1}{R_1^2} + 4\pi^2f^2C_1^2\right)}$$

The conclusion from this result is that R_1 should be as high as possible, from consideration of both Johnson noise and shot noise. In the case of the former, the improvement is progressive as R_1 is increased, the noise-component/signal ratio being proportional to $R_1^{-\frac{1}{2}}$. In the case of the shot noise, the improvement is progressive at the low-frequency end of the scale, but not at the more important high-frequency end, where the noise-component/signal ratio saturates to the value $K\pi f^{\frac{1}{2}}dfC_1(1/mi)$. This last expression reveals the very important fact that relative shot noise can only be reduced by reduction of the stray capacitance C_1.

In formulating the amplifier design it was considered undesirable to make special low grid-capacitance valves, and the lowest value of total stray capacitance that could be obtained was 17 $\mu\mu$F. Further, it did not appear to be convenient to compensate for a time-constant of more than about 20 microseconds. Hence the value of R_1 was settled at 1 megohm. In the future it is hoped to halve this capacitance and at least to double the value of R_1, which should result in a very considerable improvement in the signal/noise ratio.

(4·144) *Photo-cell Amplifier Circuit.*—Actually three amplifiers were built in the course of the development. The first, a 4-stage d.c. coupled amplifier, had to be abandoned on account of the intrinsic troubles associated with this type of coupling. The next was a 4-stage a.c. amplifier, battery-driven. With this amplifier the presence of screen after-glow was revealed, which necessitated the addition of two more stages. This amplifier, though by no means physically suited to the purpose, was used for trying out experimentally the various forms of compensating circuits, and was, moreover, gradually converted to mains operation. It provided the information necessary for the design of the final amplifier, whose circuit is shown in Fig. 7.

This amplifier consists of six stages, each of the amplifying valves (V_A, V_B, . . . V_F) being provided with a partner valve (V'_A, V'_B, . . . V'_F) operating in paraphase. The object of these apparently idle valves is threefold: (*a*) To secure low-frequency stability by balancing out the alternating currents in the decoupling condensers; (*b*) To avoid non-calculable low-frequency distortion due to the above currents; and (*c*) To reduce the amount of shielding required to secure high-frequency stability.

To avoid unnecessary stray capacitances such as would be introduced by the Miller effect with triodes, it was an obvious step to use screen-grid valves throughout. To avoid the necessity for separate voltage supplies to the screens, a further step was to make these valves screened pentodes; this permits the screens to be fed from the same decoupling condensers as the anodes, the latter actually operating at a potential below that of the screens owing to the drop in the anode load resistances. The paraphasing arrangement may be described with reference to the first amplifying stage, which is typical (and is therefore the only one fully designated in the diagram). The load resistance R_2, of about 5 000 ohms, is low compared with the plate impedance; the voltage gain is therefore mR_2, where m is the mutual conductance of the valve. This being known, the paraphasing resistance R_p is calculated, such that $mR_p = 1$. The voltage across R_p is fed through condenser C_p on to the grid of the partner valve. In order that the balanced condition shall hold at the low end of the frequency range, the coupling time-constant $C_pR'_1$ is made considerably longer than the time-constant C_2R_3, which itself is long compared with the picture period. Although ideally the valves V_A and V'_A should be matched to close limits, it has not proved necessary in practice to go to very much trouble in the matter of selection.

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* See Bibliography, (12).

With regard to the elimination of mains hum, no serious difficulty was encountered in connection with the H.T. A normal rectifier with two stages of smoothing suffices for all except the first stage, for which a further stage of smoothing (L_sC_s) is added. Heater hum was more troublesome, and was overcome by running the first five stages on direct current obtained from a rectifier.

Only two high-frequency compensating stages appear in the amplifier, namely between V_C and V_D and between V_D and V_E. These are of the type shown in Fig. 5 and discussed in Section (4·142), and are for photo-cell-capacitance and after-glow compensation respectively. The frequency range of the amplifier could be appreciably raised by adding compensation for the other stray capacitances in the amplifier, but this step is not justifiable with the present limitations of input signal strength, since any extension of the frequency band brings up the relative noise-level.

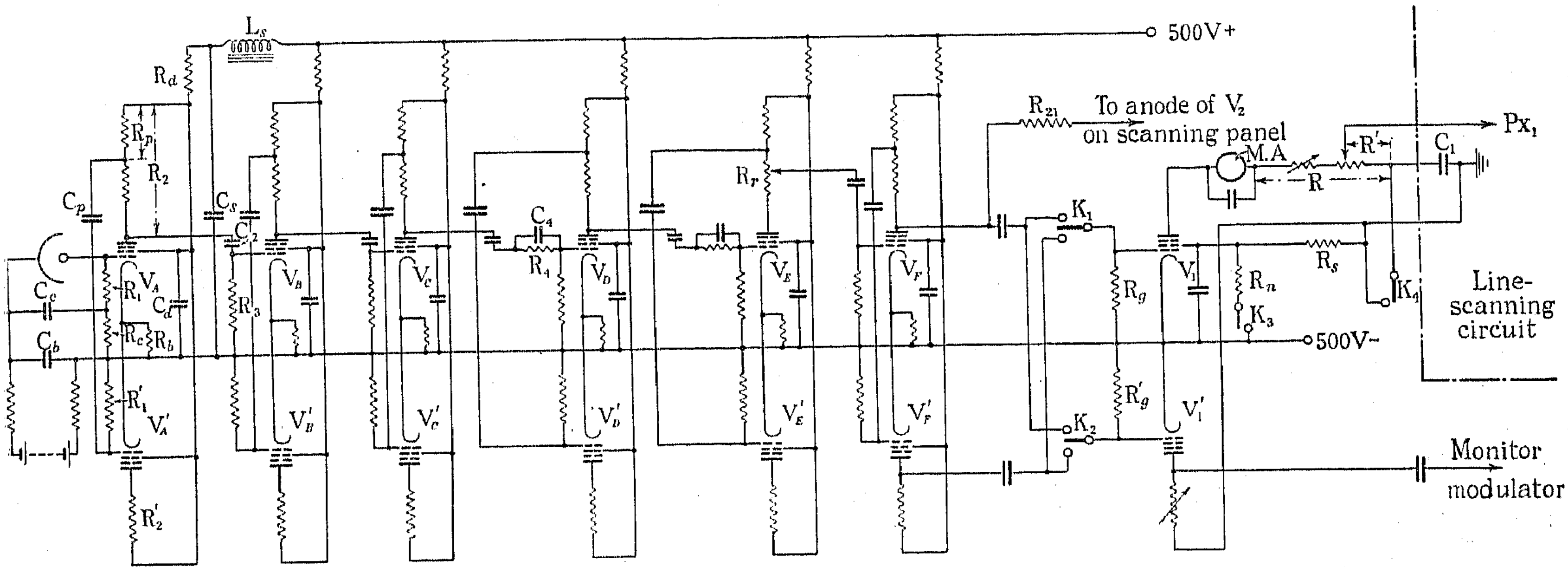

FIG. 7.—Photo-cell amplifier.

The potentiometer R_v in the anode circuit of V_E provides a calibrated gain control.

The valve V_1 belongs, as has been explained above, more properly to the scanning panel, but is located in the amplifier box in order to minimize the stray capacitance on its grid side. V_1 is also provided with a partner valve V_1', which, however, is not a paraphase valve. It serves, in fact, a variety of experimental functions, of which the most important is to simulate on the monitor tube the effect of receiver intensification.

It will be noticed that the valves V_1 and V_1' operate without any grid bias other than that set up by grid current over the grid resistances R_g and R_g'. By this artifice a very peculiar effect is introduced, namely that the d.c. component of the light signal, which is cut out by the condenser-coupled amplifying stages, is, in a manner of speaking, "faked in." This effect depends on two conditions, first that the light on the photo-cell should go to zero at least once in every picture, a condition which is easily secured by means of a barrier, and secondly that the valve V_1 should show an extremely rapid rise of grid current at the "grid current starting point." In these circumstances the grid bias always adjusts itself so that the extreme of signal corresponding to dead black is just sufficient to run the valve into the beginning of grid current; hence the grid voltage corresponding to dead black is a closely fixed quantity (near to zero), so that, in effect, the d.c. component comes through.

The key K_1 provides for transmission from positive pictures (up) or negative pictures (down); K_2 performs a similar function from the point of view of V_1'. By means of these keys it is further possible to obtain intensity-modulated pictures on the monitor tube for purposes of comparison. The setting for this is simply K_1 to neutral, and K_2 up or down according as the subject is a positive or a negative.

The keys K_3 and K_4, which are ganged together, are used for checking the noise-level of the amplifier. When the keys are closed, the screen of V_1 takes a fixed voltage, C_1 is short-circuited, and V_1 itself functions as a valve voltmeter.

(4·145) *Frequency Characteristics of Amplifier.*—Fig. 8 shows the amplitude and phase characteristics of the amplifier. These curves are obtained by calculation only, the apparatus for direct experimental verification being still under construction; experiments other than direct measurement, however, indicate that these characteristics are substantially realized in practice.

Considering first the high-frequency end, the compensating circuits are set for a 17-microsecond time-constant for the photo-cell, and a 6-microsecond time-constant for the after-glow. The four uncompensated amplifier stages have each a time-constant of 0·159 microsecond, and the two compensating circuits contribute residual time-constants of 0·343 and 0·075 microsecond and 0·205 and 0·075 microsecond respectively, these residual time-constants being obtained by arithmetically factorizing the denominators in the expressions given in Section (4·142).

From these time-constants the characteristics are easily calculated, and are shown in curves A of Fig. 8. Curves A are the effective overall characteristics, taking into account the presence and compensation of the after-glow. The characteristics as viewed from the point of view of the amplifier *per se*, that is to say from the point of view of the photo-cell current, differ from the above on account of the after-glow compensation; these characteristics, i.e. those of the amplifier proper, are shown in curves B.

Curve B of the amplitude characteristic shows how very seriously the after-glow effect increases the noise/signal ratio. Not only is the noise amplitude raised nearly eightfold at the maximum, but high-frequency components of noise which are outside the signal range come through at very high amplitudes. It has not so far been found possible to include a filter to cut out this high-frequency noise, on account of phase and time-delay considerations.

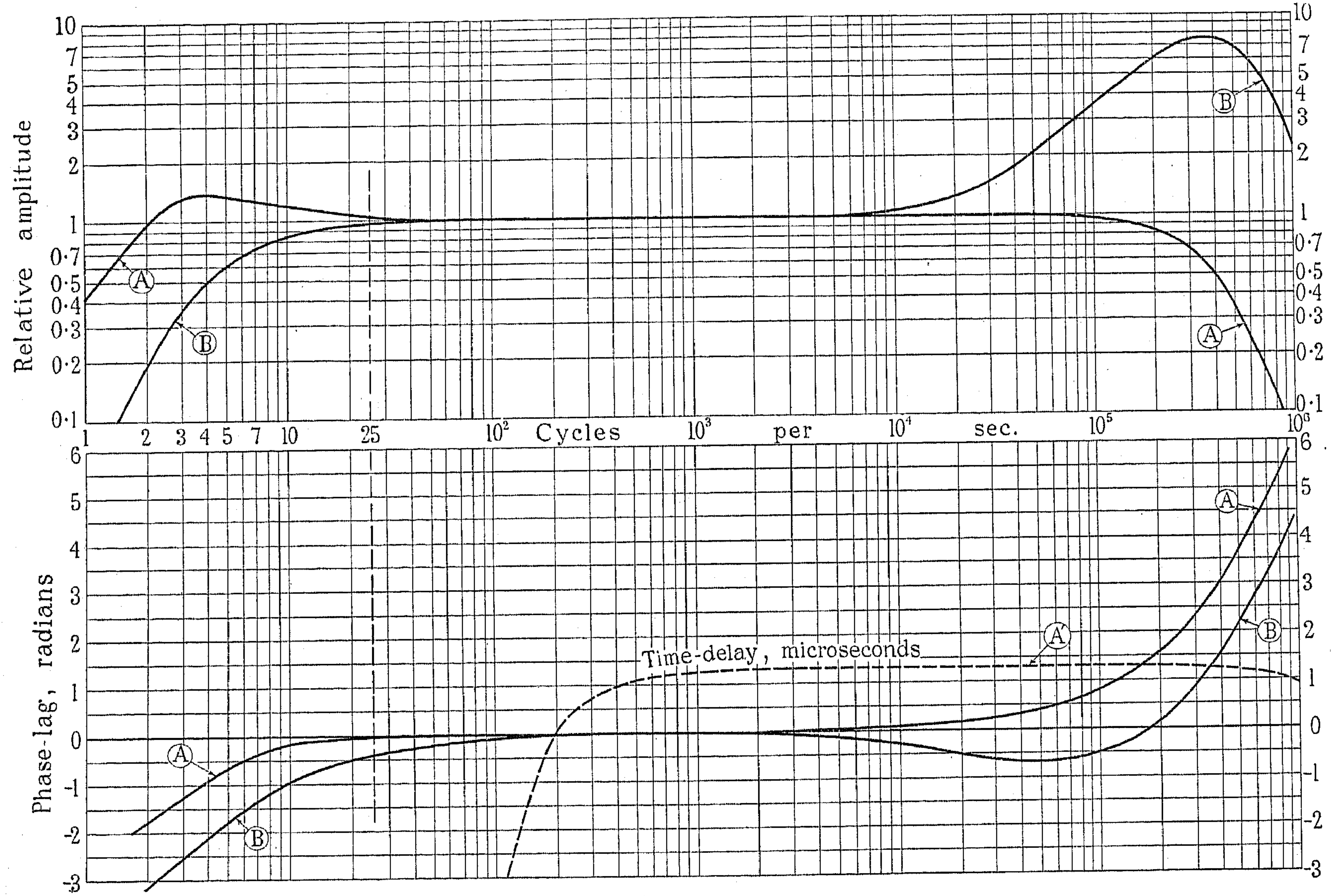

FIG. 8.

At the low-frequency end, all of the shunt capacitances are neglected, together with the effect of the high-frequency compensating circuits; the impedance of the decoupling condensers is taken to be zero, in view of the balancing effect of the paraphase valves. The only effect to be considered is then the transmission over the transfer circuits C_2, R_3, etc. As R_3 (3 megohms) is very high compared with R_2 (5 000 ohms), the fraction of the voltage passed on is

$$\frac{1}{1+\dfrac{1}{jpC_2R_3}} \quad \text{or} \quad \frac{1}{1+\dfrac{1}{jpT'}},$$

where T' is written for C_2R_3.

The six coupling circuits were originally given time-constants of 0·3 sec. each; this, however, gave too slow a low-frequency cut-off, which led to decoupling troubles. For this reason, the last two time-constants were reduced to 0·03 sec. and 0·06 sec. respectively. Curves B show the characteristics corresponding to this condition, namely four coupling circuits at 0·3, one at 0·06, and one at 0·03 sec.

The " d.c. faking effect " referred to in Section (4·144) plays a certain role at the low-frequency end which actually allows the amplifier to operate successfully with a relatively poor low-frequency characteristic. It was decided, however, to make the low-frequency characteristic as good as possible, independently of the " fake," and accordingly a compensating circuit was added to correct the above curves. This consists of a low-frequency compensating circuit at the photo-cell input, namely the compensating condenser C_c and isolating feed resistance R_c (see Fig. 7). The operating factor of this compensation is easily found to be

$$\frac{1+\dfrac{1}{jpC_cR_1}+\dfrac{1}{jpC_cR_c}}{1+\dfrac{1}{jpC_cR_c}}$$

or

$$\frac{1+\dfrac{1}{jpT_c}+\dfrac{R_1}{R_c}\cdot\dfrac{1}{jpT_c}}{1+\dfrac{R_1}{R_c}\cdot\dfrac{1}{jpT_c}}, \quad \text{where } T_c = C_cR_1.$$

Thus, provided R_c is high compared with R_1, the circuit gives compensation for a single time-constant T_c.

In the present case, this is made equal to the equivalent coupling time-constant of the whole amplifier, 0·0158 sec. Curves A show the low-frequency characteristics after this compensation has been included.

Owing to the logarithmic frequency-scale, the linearity of phase displacement with frequency is not apparent. To show this, the curve A′ has been added, which gives the time-delay, i.e. the ratio of phase lag to angular frequency. This is seen to stay remarkably constant over the high-frequency end of the working range. At the low-frequency end the value of the time-delay changes rather abruptly to a time-advance, as is to be expected. The constant value of the time-delay in the high-frequency region is actually 1·33 microseconds.

(4·146) *Effect of Finite Time-delay.*—The above time-delay of 1·33 microseconds is too long, and needs to be improved by compensation of the individual anode circuits as soon as the signal/noise ratio is sufficiently improved. This time-delay implies that a certain interval, of the order of 1·33 microseconds, must elapse before the control signal can get back to the spot. Strictly speaking, we have to add to this time the total loop length divided by the appropriate transmission velocity; this latter amounts to approximately 0·02 microsecond. This time is negligible in comparison with the amplifier time-delay, but indicates the lowest limit that could ever be reached.

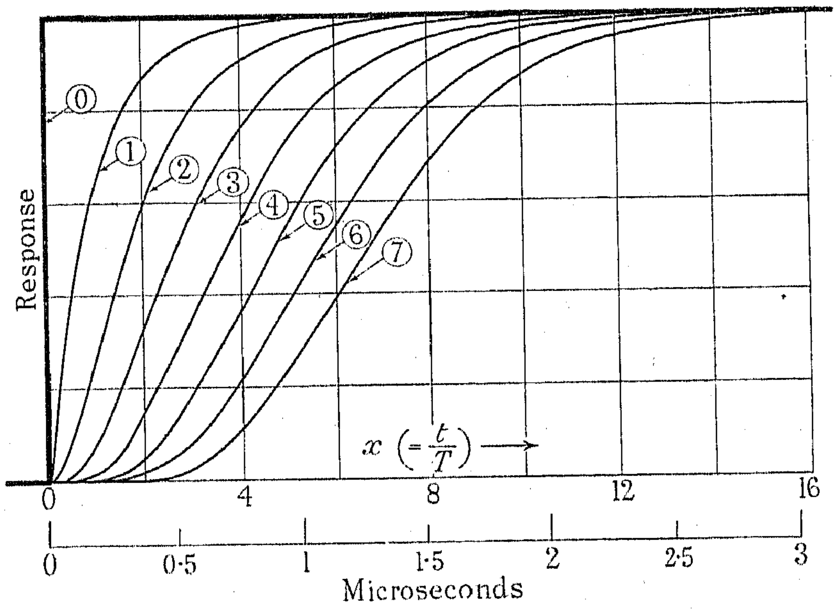

FIG. 9.

On the basis of 25-cycle pictures and 19 200 picture points, the average picture-point time is 2·08 microseconds. Supposing that the scanning speed in the dark places is 4 times the average speed, the shortest picture-point time is 0·52 microsecond. Hence the total time-delay ought to be reduced to a quantity smaller than this. If intensification is not used, the maximum scanning speed must amount to much more than 4 times the average, in which case the effect of the time-delay becomes aggravated.

(4·147) *Transient Aspect of Amplifier.*—Although the amplitude and phase characteristics contain implicitly the whole information as to the behaviour of the amplifier, it is not entirely an easy matter to deduce from them the response of the amplifier to a transient. The authors have found it useful to keep the latter point of view closely in mind, and to facilitate this an attempt was made to calculate directly the response to a transient of the Heaviside type, namely an input voltage which is 0 for $t < 0$ and equal to a constant v_0 for $t \geqslant 0$. This calculation falls into two sections; first the response during the first few microseconds of the transient, during which time the long time-constant coupling circuits play no part, the response being determined by the short time-constants of the anode circuits and compensating circuits; secondly the response during the following few hundredths of a second, the short time-constant effects having settled down to a stationary condition, the response being now determined only by the long time-constant coupling circuits. These two sections of the response correspond respectively to the high-frequency and low-frequency ends of the frequency characteristic.

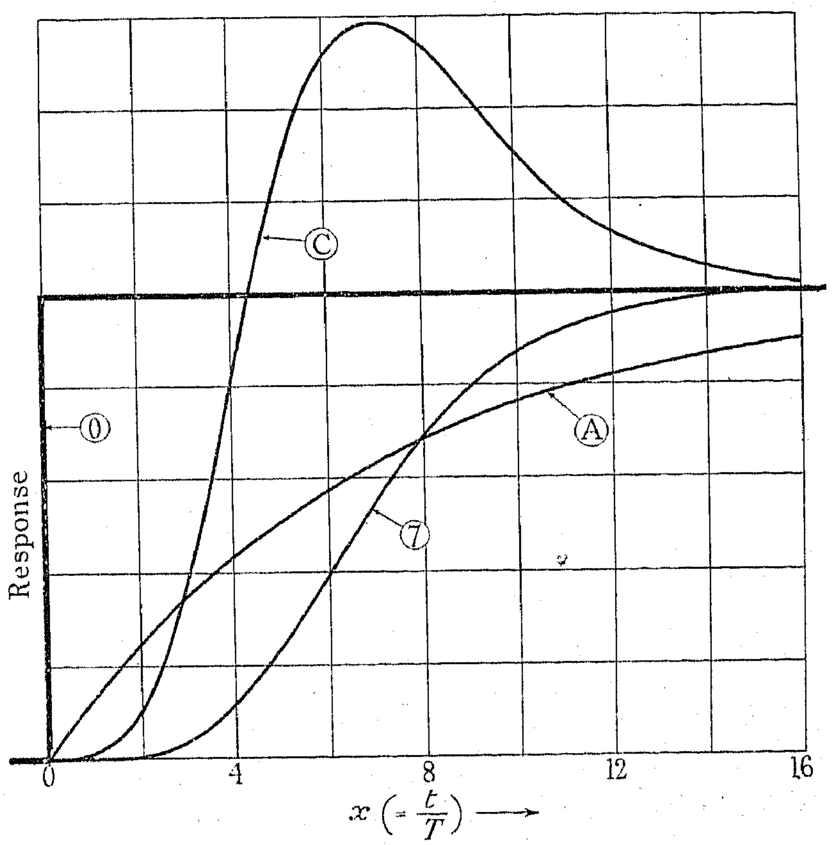

FIG. 10.

When these calculations are attempted, it immediately becomes evident that, although there are no intrinsic mathematical difficulties, the labour is prohibitive for more than about three stages; further, that the mathematical expressions which appear are very unsuitable for numerical calculation. There is one condition, however, in which both the mathematics and the arithmetic become very much simplified, and that is when all the circuits have the same time-constant. Because of the intrinsic interest of these two cases, namely equal shunt time-constants T and equal coupling time-constants T', the following results are given.

(*a*) High-frequency end:

If there are n equivalent circuits each of time-constant T, the solution is

$$v_n = v_0\left[1 - e^{-x}E_n(x)\right]$$

where x is written for t/T, and $E_n(x)$ means the first n terms of the expansion of e^x, namely

$$1 + x + \frac{x^2}{2!} + \ldots + \frac{x^{n-1}}{(n-1)!}$$

This peculiarly simple result is worked out as far as the case of 7 equivalent circuits, and is exhibited in Figs. 9 and 10. Fig. 9 shows a family of 8 curves (numbered 0 to 7); the discontinuous curve 0 is the transient itself, and curves 1, 2, . . . 7, show how it appears after 1, 2, . . . 7, stages of "distortion" with time-constant T. If the photo-cell amplifier is regarded as equivalent to 7 stages each of 0·19 microsecond time-constant, the appropriate time scale for this particular case may be drawn in the diagram. Fig. 10 shows the transient and a specimen curve (7) together with a comparative curve (A) giving the response of a single stage with 7 times the time-constant. Curve C in the diagram shows the effect of endeavouring to compensate curve 7 with the compensation appropriate to curve A. The hump which appears in curve C shows up in a television picture as exaggeration of the contrast at the transitions, or "harsh boundaries."

(*b*) Low-frequency end:

The result is given for purposes of record, the application to the present photo-cell amplifier being hindered by the inequality of the coupling time-constants. For n coupling circuits, each of time-constant T', the solution is expressed in the inductive form

$$v_n = v_0 e^{-x} f_n(x),$$

where x is written for t/T', and

$$f_n(x) = f_{n-1}(x) - \int f_{n-1}(x)\,dx$$

$$\vdots$$

and $$f_1(x) = 1$$

This inductive formula leads to the following:—

$$v_1 = v_0 e^{-x}$$

$$v_2 = v_0 e^{-x}(1 - x)$$

$$v_3 = v_0 e^{-x}(1 - 2x + \tfrac{1}{2}x^2)$$

$$\vdots$$

$$v_6 = v_0 e^{-x}(1 - 5x + 5x^2 - \tfrac{5}{3}x^3 + \tfrac{5}{24}x^4 - \tfrac{1}{120}x^5)$$

Fig. 11 shows a plot of certain of these results. Curve 0 is the transient itself; curve 1 is the response after a single coupling circuit of time-constant T'; and curve 6 is the response after six such circuits. Curve A is the response of a single coupling circuit of time-constant $T'/6$, which is seen to coincide with curve 6 over a sufficiently short time-interval, but not over a long time-interval.

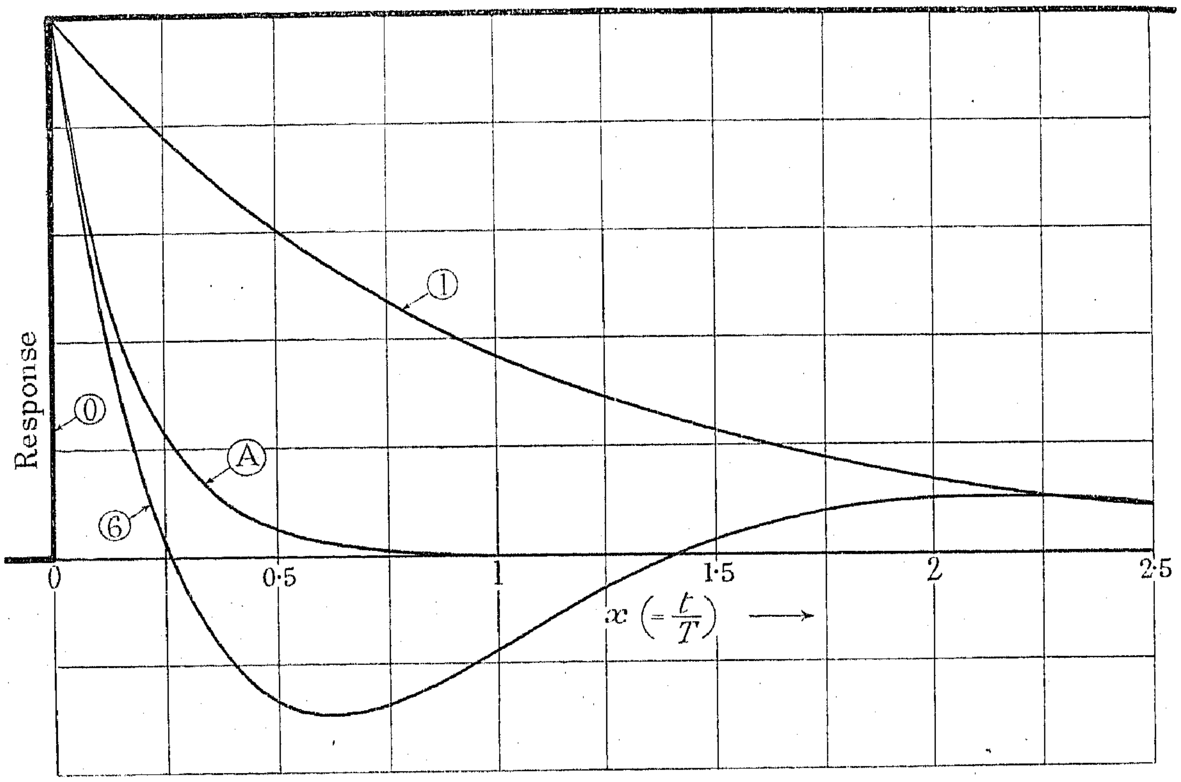

FIG. 11.

(4·15) *After-glow and Aperture Measurements.*

The measurement of after-glow times of a few microseconds is not intrinsically an easy matter, but the authors have found a simple solution to the problem in making the television transmitter serve as its own measuring apparatus. For this measurement the key K_1 of the amplifier was set to the neutral position so as to provide uniform line-scanning, K_2 was thrown to the up position, and the voltage on the anode of V_1' was examined on an oscillograph. The latter was actually the monitor tube, the normal paralleling of its X plate to that of the transmitter being left unaltered, so as to provide directly a synchronized time-base motion. Instead of a picture, a barrier was inserted in the film gate so as to mask off sharply one-half of each of the scanning lines.

With an infinitely small scanning spot, the signal on the photo-cell is thus simply a repetition of curve 0 of Fig. 9. In the case of a finite circular scanning spot this "transient" is modified to the form of curve 0 of Fig. 12. At normal scanning speeds the output of the amplifier does not show exactly this wave-form, but departs from it in the same way as, for instance, curve 7 departs from curve 0 in Fig. 9. If, however, the scanning speed is progressively reduced, the output wave-form closes down to the shape of curve 0 in Fig. 12, this curve expressing simply the "aperture effect." At sufficiently low scanning speeds this statement remains true even when the after-glow compensation is removed by setting to zero the condenser C_4 in the second compensating circuit. Then if the scanning speed is raised, the output wave-form on the oscillograph is seen to change to the form of curve 1 in Fig. 12. Curve 1 can now be brought back to coincide with curve 0 by increasing the value of capacitance C_4. This condenser value is then measured, and the product C_4R_4 gives the time-constant of the after-glow. This process is only applicable provided the time-constant to be measured is reasonably long compared with the time-constant of the whole amplifier, as the method requires it to be possible to select a scanning speed at which the after-glow effect is shown up whilst the amplifier characteristic remains substantially perfect.

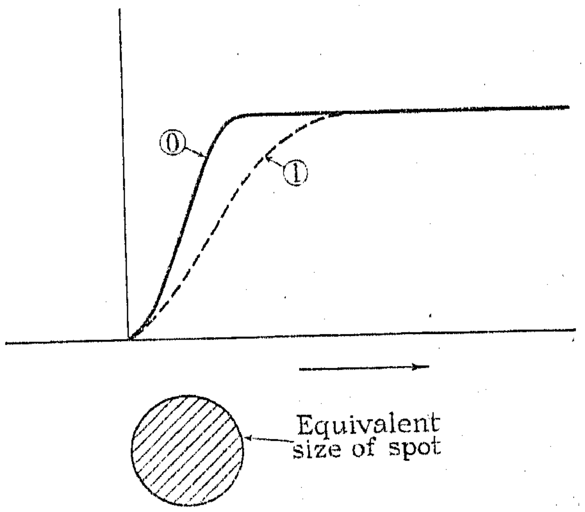

FIG. 12.

Whilst the above experiment is extremely instructive, it is in practice possible to perform almost the same measurement on an actual television picture. The scanning is first slowed down, only a fraction of the picture being covered; and the optical focus of the transmitter tube, and electrical focus of transmitter and monitor, are set to optimum. The satisfactory definition of the picture in this condition indicates that the aperture effect is not troublesome. Then the scanning is speeded up and the second compensating circuit is adjusted to give optimum picture definition without harsh boundaries. The time-constant C_4R_4 of the second compensating circuit is then the time-constant of the after-glow. As the scanning speed is raised still higher, the definition again begins to fall away owing to the high-frequency droop of the amplifier.

(4·2) THE TRANSMISSION LINK.

A satisfactory velocity-modulated picture having been achieved on the transmitter tube, and, indeed, an enlarged and intensified version of it having been produced on the monitor tube, the next problem is to select a point in the transmitting circuit from which to take the transmission signal. According to the ideas of Thun, and also originally to those of the authors, the signal to be transmitted was essentially the voltage on the line-scanning deflector plate (P_{X1}) of the transmitter. When R and R' (in Fig. 3) are made equal to zero, this voltage is the same as that on the anode of V_1. The condenser-resistance potentiometer $C_{16}\,C_{60}\,R_{16}\,R_{60}$ provides a faithful copy of the anode voltage of V_1 at a convenient level (about 2 volts swing). This voltage is stepped down to a low impedance by means of the valve V_6 and passed out on to a 500-ohm line. This line would ultimately lead to the input of the radio transmitter, but in the present case it leads directly to the receiver.

There exists, however, a serious disadvantage in deriving the transmission-signal voltage directly from the line-scanning voltage, a disadvantage which was first explicitly pointed out by von Ardenne. Although the radio transmitter may be modulated to a high percentage, the modulation corresponding to a single picture point is only a small fraction of this percentage; hence the picture detail is liable to serious disturbances from interfering voltages. To overcome this disadvantage, von Ardenne has proposed to treat as the transmission signal not the voltage on the anode of V_1, but the voltage on the grid of this valve. This means, however, that the implicit synchronism which is such an attractive property of the velocity-modulation principle, is sacrificed. Investigations made by the authors* have shown, however, that by reason of the fact that the voltage transmitted according to this proposal is still in the nature of a scanning voltage, the synchronization problem allows of an extremely simple solution; but that the proposal itself is accompanied by the following very serious practical difficulty. The proposal contemplates a receiving circuit very closely analogous to that at the transmitter, and comprises the equivalent of the time-base circuit $V_1\,C_1\,V_2$; to the grid of V_1 is to be fed an exact copy of the corresponding voltage at the transmitter; the successful operation of the system therefore requires not only an extremely accurate copy of the potential on the grid of V_1, but also that the anode-current/grid-voltage characteristics of the two valves should be accurately matched over the whole of their working range. Departure from these conditions results in very serious picture-distortion.

The solution adopted by the authors, and which is free of these difficulties, may best be introduced by expressing the above disadvantage in a rather different form. The voltage across the condenser C_1 is obtained from the signal on the grid of V_1 by a species of integration process, which means that the higher-frequency components of the signal are relatively attenuated. This does not imply distortion, but merely that with progressive reduction of the field strength at the receiver the higher-frequency components are the first to drop below the noise-level. To overcome this disadvantage the signal voltage is made to consist of two components directly superposed, namely a voltage proportional to the displacement, and a voltage proportional to the velocity, of the scanning spot.

The introduction of the resistance R in Fig. 3 provides on the anode of V_1 exactly such a voltage. Referring back to Fig. 2, the wave-form (*b*) is the displacement voltage; the wave-form (*c*) is proportional to its derivative, and is in fact the voltage across the resistance R; the wave-form (*d*), which is the superposition of these two wave-forms, represents the transmitted signal. At the receiving end these two voltage components may be separated out and led to perform their proper functions of spot displacement and intensification respectively. This separation, which is only possible in view of the fact that the one component is proportional to the time derivative of the other, is effected by a circuit which is shown schematically in Fig. 13. In this circuit V is a high-impedance valve whose anode faces a resistance R_0, which latter is shunted to earth via condenser C and a small resistance R″. If R″ is made vanishingly small, and if the time-constant CR_0 in Fig. 13 is made equal to the time-constant C_1R in Fig. 3, then it comes about that when a voltage wave corresponding to Fig. 2(*d*) is applied to the grid of the valve V, a voltage corresponding to that of Fig. 2(*b*) appears on the anode whilst a voltage proportional to that of Fig. 2(*c*) appears across R″. By choice of the time-constant C_1R at the transmitter, the relative amplitudes of the displacement and the velocity components can be set to any desired value.

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* See Bibliography, (13).

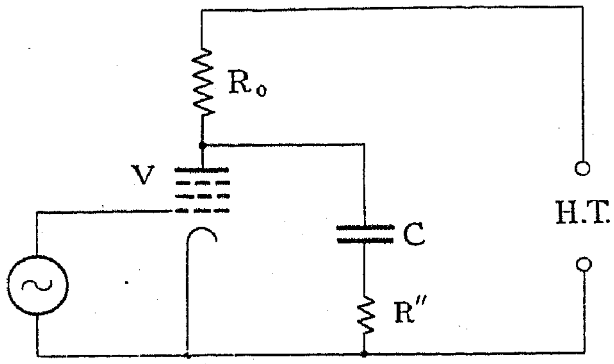

FIG. 13.

The feature of this form of signal voltage is that it contains a component which is not attenuated with frequency.

To establish that the circuit of Fig. 13 actually does separate out correctly the two superposed components, we have only to note that the impedance facing the plate of the valve V is

$$R_0\frac{1+jpCR''}{1+jpC(R_0+R'')}$$

which becomes, when $R'' \to 0$,

$$R_0\frac{1}{1+jpCR_0}$$

This is the correct form of operator for reproducing the scanning voltage from the compound signal. The more accurate expression, taking into account the finite value of R'', shows that the operator should more strictly be taken as

$$\frac{1}{1+jpC(R_0+R'')}$$

whilst in addition the operator $(1+jpCR'')$ appears in the numerator. This can be made to compensate the high-frequency loss of the previous stage, although in practice both the latter and its compensating factor are of rather small account. If v is written for the voltage across R_0, the voltage across R″ is easily found to be

$$R''\frac{1}{1+jpCR''}\cdot\frac{dv}{dt}$$

Thus the finite value of R'' introduces a small high-frequency droop into the intensification voltage, which may, if desired, be compensated in a later stage.

The peculiar advantages of this compound form of transmission signal accrue at the receiver. At the transmitting end the advantage is with the simpler arrangement on the lines of that devised by Thun, as will be seen from considering the modulation conditions on the radio transmitter. In the case of a signal such as that of Fig. 2(*b*) we have the unique advantage of absolutely constant percentage modulation for the radio transmitter, because the extremes of signal correspond simply to the lateral boundaries of the picture, which do not vary. With a signal such as that of Fig. 2(*d*), a variable component is added to the modulation; but in practice this variation is relatively small because the upper extremity corresponds to the full picture displacement, plus a component corresponding always to "black." This is because the spot has always to overrun to a small extent the boundary of the picture proper and pass behind a barrier. Thus the only variations in this component are those due to the functioning of the automatic monitor on the screen of V_1. At the lower extremity, which corresponds to the end of the fly-back, conditions are always the same. The modulation conditions in the present case can therefore be described as nearly, but not quite, constant percentage modulation.

A further complication is introduced at the transmitter when the resistance R is introduced for the purpose of yielding the compound signal. In the simpler case of $R = 0$, the several stray capacitances from the anode of V_1 to earth come directly in parallel with the condenser C_1, and so simply constitute part of the charging condenser of the time base. When the resistance R is introduced, these stray capacitances are no longer in parallel with C_1', and part of the time-base charging current is diverted from the condenser branch proper. This effect, which by appropriate design can be kept small but not negligible, can be compensated by the inclusion of the resistance R′, such that

$$(C_1+C')R' = C'R,$$

C' being the total stray capacitance from the anode of V_1 to earth.

(4·3) THE TELEVISION RECEIVER.

This section is concerned only with the television part of the receiver, and not with the radio portion; the television portion is, however, designed to work from a low level of signal voltage such as could easily be obtained from a detector.

The receiver comprises in principle a separating circuit such as that of Fig. 13, for separating out the displacement and velocity components of the signal, a line-scanning amplifier for the displacement voltage, giving a sufficient voltage output for providing the horizontal scanning, a ratcheted time-base for the picture-traversing, and an amplifier for the velocity-component voltage for intensification.

For the type of oscillograph contemplated, the picture size is approximately 440 × 330 volts. The 330-volt swing is the sweep of the ratcheted time-base, whilst the 440-volt swing is the output of the line-scanning amplifier. In order to avoid having to provide an inconveniently high H.T. voltage for so large a voltage swing, a paraphase drive for the P_X deflector plates suggests itself. This reduces the voltage swing per anode to 220 volts, and a 500-volt H.T. supply is adequate for both this and the 330-volt time-base sweep. The paraphase arrangement of the line-scanning amplifier is also an advantage from the point of view of avoiding low-frequency distortion, which latter has necessarily to be kept down to a very low level in order to avoid misshaping of the picture.

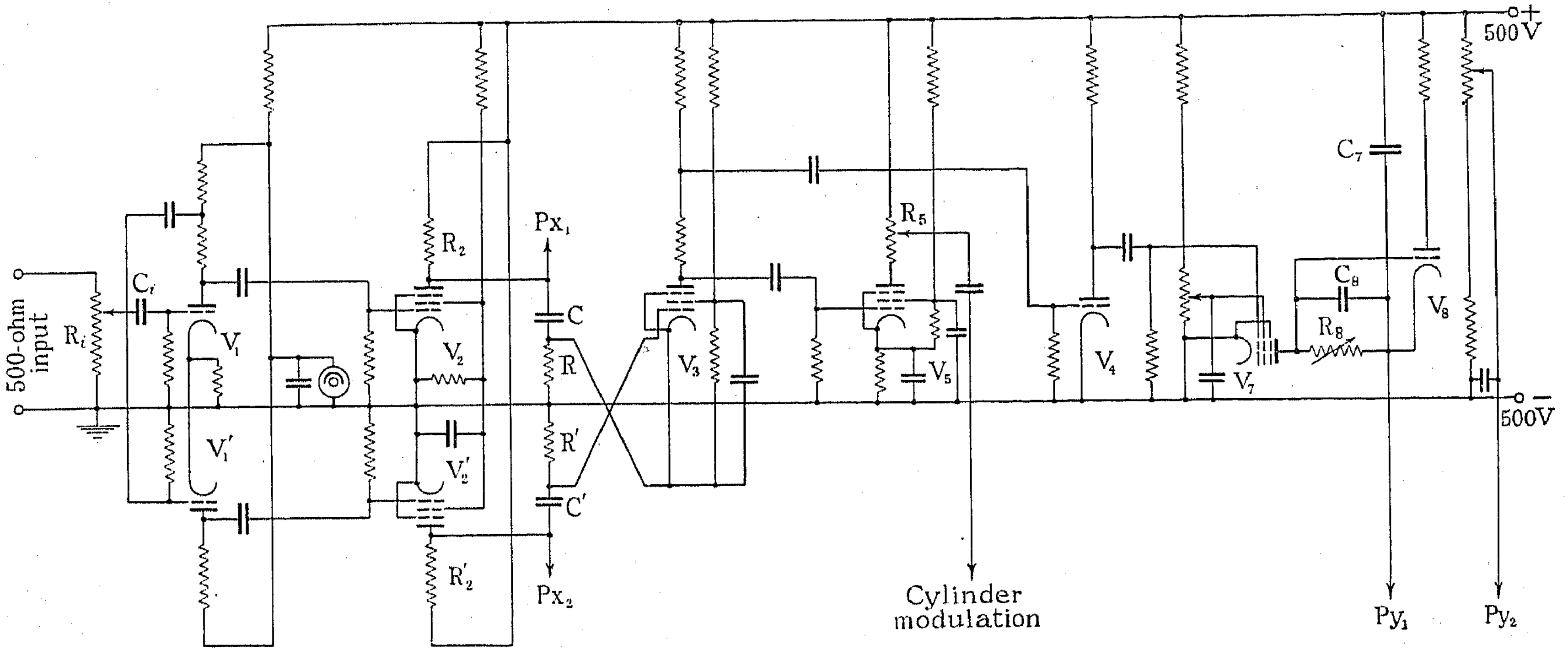

FIG. 14.—Receiver.

(4·31) *Circuit Arrangements.*

In the practical receiver, whose circuit is shown in Fig. 14, the separating stage is combined with the paraphase output stage of the line-scanning amplifier. The input, which is fed straight from the wire-line on to a 500-ohm potentiometer R_i, is tapped off at a suitable level and passed via a blocking condenser C_i on to the grid of valve V_1. The latter drives its paraphase partner V_1' in the same manner as that described for the photo-cell amplifier at the transmitter. The anodes of V_1 and V_1' are fed from a common decoupling circuit, the condenser of the latter being shunted by a neon stabilizer tube for the purpose of smoothing out mains fluctuations on this stage. The anode of V_1 supplies a small-scale copy of the compound voltage on the anode of V_1 at the transmitter, whilst V_1' supplies a similar copy in opposite phase. These two anodes drive the grids of the paraphase output valves, the latter being screened pentodes. The anodes of these pentodes are connected directly to the P_{X1} and P_{X2} deflector plates of the receiving oscillograph and face the equal resistances R_2 and R_2'; the latter are shunted by equal condensers C and C′ and low resistances R and R′ to earth. The time-constants $(C + C_s)R_2$ and $(C' + C_s)R_2'$ are each made equal to the time-constant C_1R at the transmitter, C_s being the stray capacitance in each case. Herein lies an incidental but extremely important advantage of the compound form of signal, for the resistances R_2 and R_2' can be made relatively high, e.g. from 30 000 to 50 000 ohms, which could not be done in the case of the simple displacement signal on account of frequency-characteristic droop; in the present case, frequency-characteristic droop is actually required and has to be encouraged by increasing the stray capacitances several-fold with the condensers C and C′. Because of this high output-resistance the gain of the output valves is high, the grid swing is small, and the valve characteristics do not depart seriously from linearity; such distortion as does occur is cancelled out by the paraphase arrangement.

Across the resistances R and R′ appears a voltage proportional to the instantaneous scanning velocity. This is passed through two amplifying stages V_3 and V_5, and provides the intensification voltage which is taken on to the Wehnelt cylinder of the oscillograph. The valve V_3 also drives a further valve V_4, which acts as ratchet driver for the picture-traversing circuit. The latter consists of components strictly analogous to the picture-traversing circuit at the transmitter, namely the ratcheted charging valve V_7, the time-base condenser C_7, and the discharge thyratron V_8; the latter is biased by the time-constant circuit C_8R_8, which is again wholly analogous to that at the transmitter, the time-constant being adjusted so as to allow V_8 to fire within the delay interval in the scanning sent out by the transmitter.

The controls at the receiver are extremely simple. The input potentiometer R_i is adjusted to give the required picture breadth, and the screen voltage of the valve V_7 is then set to give the required picture depth, which it does by varying the pitch of the raster. There is no synchronizing adjustment because the values of R_8 and C_8 will be fixed. The remaining controls are "intensification volume control," namely the potentiometer R_5, and oscillograph focusing, namely the cylinder-biasing potentiometer.

The above adjustments can of course only be made while the signal is actually being transmitted. It might be supposed that if the transmission were cut off, the spot on the receiving oscillograph would come to rest and so possibly damage the screen. This in practice is not the case, because as soon as the transmission is cut off, the ratchet driver V_4 ceases to pulse, and the grid of V_7 rapidly slides to zero voltage and causes a traversing movement to start up on its own account, thus preventing the screen from being damaged.

A further feature of importance is that the valves V_2 and V_2' are given no applied grid bias, but are allowed to find their own bias by means of grid current. This arrangement provides a d.c. faking effect similar to that described for V_1 at the transmitter. Such a d.c. fake is necessary, because in its absence the line-scanning waveform would tend to set itself with its " centre of gravity " in a fixed location, the moving of this centre of gravity being tantamount to the transmission of direct current; such a movement is necessary if the lateral boundaries of a moving picture are to stay in a fixed position. By operating without an applied grid bias, matters adjust themselves so that the two extremes of signal correspond to the respective starting-points of grid current on the two valves. That is to say, definite anode voltages on the valves V_2 and V_2 are associated with the boundaries; and since there is d.c. transmission between these anodes and the deflector plates, the picture boundaries remain stationary.

(4·32) *Shape of Intensification Curve.*

In order to decide on the proper shape of intensification curve, it is necessary to revert to the transmitter and consider the shape of the V_1 charging-current characteristic. It will be recalled that matters are so arranged at the transmitter that, in the case of transmission from a positive, the condition of no light on the photo-cell corresponds very closely to zero grid voltage on V_1, whilst increasing light on the photo-cell causes the grid voltage to become negative. In these circumstances, and assuming that the amplification is linear up to the grid of V_1, that is to say assuming no *amplitude* distortion, it follows that the ideal theoretical shape for the V_1 anode-current/grid-voltage characteristic is the rectangular hyperbola $i = k/(-v_g)$, curve A of Fig. 15.

Such a curve, giving an infinite current at zero grid voltage, cannot of course be obtained in practice; and even if an approximation to it, namely a curve with a very steep rise of anode current in the region of zero grid voltage, could be obtained, the correspondingly high scanning velocities would be objectionable, on the grounds stated in Section (4·146). In the low-current region of the curves, however, the hyperbolic shape can be approximately realized by the now common " variable μ " type of characteristic. Such a characteristic is shown in curve B of Fig. 15. In order to obtain faithful tone reproduction, the difference between curves A and B has to be made good by intensification.

In Fig. 15, the ordinate in the positive direction is primarily a scale of V_1 charging current (i), and the abscissa in the negative direction is a scale of V_1 grid voltage. The ordinate, however, can equally well be regarded as a scale of instantaneous scanning velocity (u). If we now make the abscissa in the positive direction a scale of relative spot-intensity (at the receiver), the top right-hand quadrant is suitable for drawing-in the intensification curve. This is done in curve C of the diagram. Over the range of velocity in which curves A and B coincide, the intensification is not required to function; the spot remains at full intensity as indicated by the value 1 in curve C. For velocities which are less than that corresponding to the hyperbolic curve, the intensification should be such as to cut the spot intensity to the appropriate ratio, this ratio becoming zero at the velocity corresponding to zero grid voltage on V_1. In the region of negative velocity corresponding to the fly-back, the shape of the intensification curve is immaterial provided the fly-back is sufficiently rapid. In the present case, however, the inclusion of the resistance R in the condenser circuit of the transmitter has the effect of slowing-down the fly-back to some extent, and it is therefore preferable to arrange for the intensification curve to show a cut-away in the region of negative velocity, as indicated by the dotted curve C′.

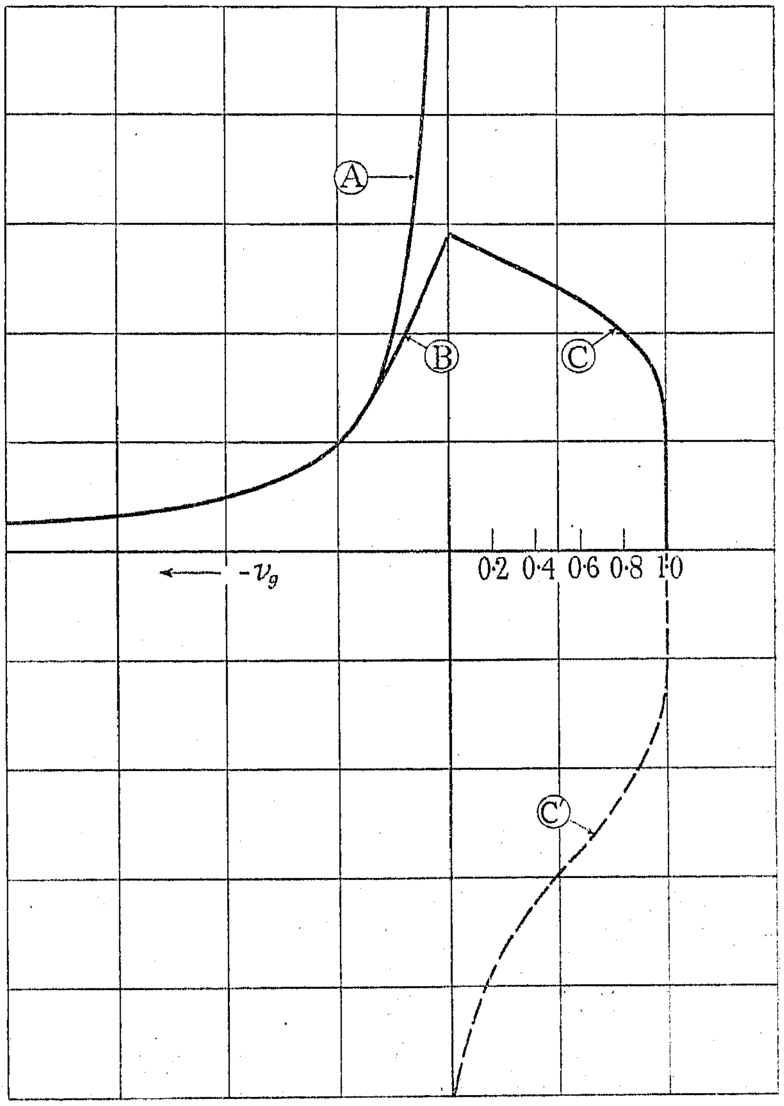

FIG. 15.

The detailed shape of this intensification curve appears, on experiment, to be of academic rather than of practical importance, as satisfactory pictures are obtained in spite of serious departures from the theoretical shape. The general form, however, should be preserved, namely that

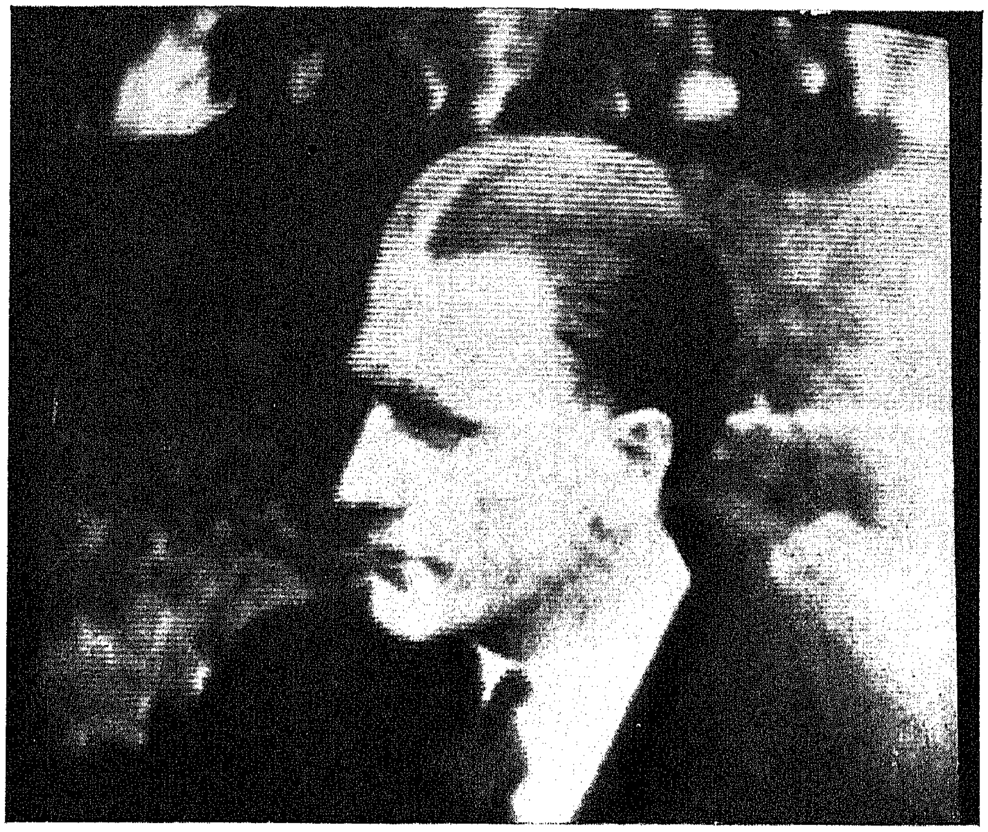

Fig. 16.—Reproduction of photograph (December, 1933).

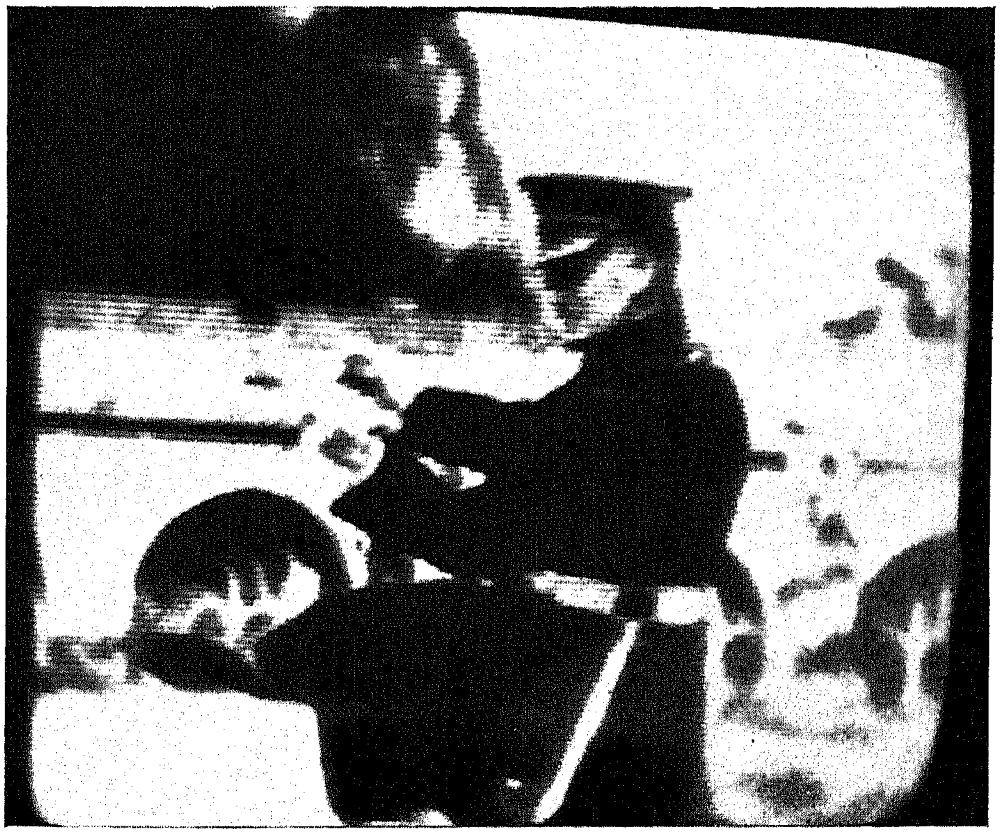

Fig. 17.—Reproduction of photograph (December, 1933).

[Note.—The above photographs should be viewed at a distance of 4–5 ft.]

the intensification should not function in the brightest portions of the picture, and that the curve should cut away for extremes of scanning velocity, both positive and negative. In the present receiver, this state of affairs is approached by working the valve V_5 (see Fig. 14) well down the bend of its characteristic, relying on the modulation curve of the oscillograph to give a partial cut-away for negative velocities.

(5) RESULTS AND PROSPECTS.

Specimens of results to date (December, 1933) are shown in the photographs, reproduced in Figs. 16 and 17 (see Plate facing page 80), of pictures of about 120 lines. The photographs are intended to convey some idea of the available detail, but they give an unfavourable representation of results. In the first place a picture viewed on the tube appears, partly on psychological grounds, much more acceptable than a photographic reproduction. Secondly the addition of motion, and to a less extent the addition of sound, make a very surprising difference to the " intelligence " carried by the picture. In order to convey a more representative indication of results, a cinema film is being prepared, photographed frame by frame off the receiving tube, which provides a short demonstration of moving subject matter.

The number of lines that can be used, at present limited to about 140, is determined by two factors: (*a*) the signal/noise ratio in the photo-cell amplifier, and (*b*) the size of the scanning spot on the film. These two effects are closely linked together, for the size of the scanning spot on the film can always be reduced by increasing the magnification ratio of screen picture-size to film picture-size; this, however, entails a loss of light, so that the limit is eventually again determined by signal/noise ratio.

When the noise of the amplifier has been reduced to its theoretical minimum, there remain two possibilities for improvement; first by improving the photo-cell sensitivity, and secondly by improving the transmitter tube itself. The latter possibility is extremely promising and will without doubt shortly be put into effect in the form of reduced after-glow, increased light value, and possibly reduced size of scanning spot. That such improvements are possible will scarcely be doubted when it is recalled that the results so far obtained have been with a transmitter tube which is simply the standard " measuring " type of oscillograph* without any modification whatever.

From the point of view of the transmitter-tube possibilities, there seems to be no doubt that the number of scanning lines could be raised to at least 150–200, at which latter value the theoretical detail approaches that of the home cinema; in the opinion of the authors the entertainment values become comparable at a considerably lower number of lines, say 100–150.

The present basis of operation at the transmitter appears to limit the picture subject-matter to film material. As previously mentioned, this restriction is not considered to be of much significance, because a television service is subjected to the same limitation on account of the following considerations. (*a*) Owing to the large frequency band the service must necessarily be on ultra-short waves, i.e. below 9 metres; this means a short transmission range, and so a moderately large number of local transmitters. The subject matter must therefore be in a form which can be easily sent about from place to place. (*b*) Topical events must constitute an important item of an entertainment television service, and only a negligibly small proportion of these can be " brought into the studio." Direct television transmission from the site, even if it were technically possible, would hardly be of much value on account of considerations of " time of day."

In spite of the above arguments there is a rooted inclination to demand the television of direct subject matter, and it is therefore desirable to consider what are the possibilities of modifying the velocity-modulation transmitter to handle such material. Although the construction of a " giant " oscillograph for direct subject illumination is not inconceivable, a more promising line of approach appears to be offered by a reversion to a process analagous to the " floodlight " system, in which a real image of the flood-lit subject is scanned. Methods of achieving this process on a cathode-ray scanning basis have been indicated by Farnsworth* and by Zworykin,† and either of these seems to be basically suitable for application to the velocity-modulation principle.

At the receiving end, the oscillograph tube is again the dominating consideration. Whilst the system has been developed in terms of the present type of " measuring " tube, and whilst acceptable results are so obtained, it is the fact that these tubes are in many respects unsuitable. Very considerable improvements may be looked for with the development, now in hand, of a " hard vacuum " oscillograph for the receiver. It is in expectation of this development that no measures have been taken to circumvent the origin distortion effect,‡ which is an objectionable feature of the present tubes. The new tube, moreover, must be indirectly heated and must show better modulation characteristics than the average tube of the present type.

As regards screen size, the authors regard a 9-in. diameter screen as a satisfactory compromise between what is desirable and what is practical, and tubes of this size have already been made. The electrode structure required for the wide-angle deviation in these tubes has presented a certain amount of difficulty, but this matter is in abeyance pending the hard-vacuum tube development.

For still larger picture size, and when cost is not a ruling factor, the possibility of optical projection from a relatively small fluorescent screen may be considered.

As regards screen materials, a wide range has been examined, and a mixture evolved which gives a satisfactorily white-light response. Other materials which are now coming to hand, however, indicate that it will be possible to effect a substantial increase in the luminous efficiency.

In conclusion, it is thought that the results obtained to date indicate that the system has reached a practical footing, and that the fact of this having been achieved in a relatively short time, and with standard but ill-suited oscillographs, is a vindication of the fundamental merits of the system. The completion of the above-mentioned tube developments may be expected to effect a substantial improvement on the results at present obtainable.

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* See Bibliography, (14).

* See Bibliography, (15). † *Ibid.*, (16). ‡ *Ibid.*, (17).

(6) ACKNOWLEDGMENTS.

The authors wish to acknowledge their indebtedness to Mr. W. R. Bullimore, managing director of Messrs. A. C. Cossor, Ltd., who sanctioned both the work and its publication, and whose keen personal interest in the development has been a standing encouragement. They also wish to acknowledge the assistance of their various colleagues in the Cossor company, but especially that of Mr. W. H. Stevens, who personally constructed the major part of the experimental apparatus.

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[The discussion on this paper will be found on page 83.]

DISCUSSION BEFORE THE WIRELESS SECTION, 7TH FEBRUARY, 1934.

Mr. J. F. Herd: The authors are to be congratulated on the presentation of a paper containing such an amount of technical information and detail, and on the rapid development of a practical television system giving the results which have been shown in the film. The combination of velocity-modulation and intensity-modulation appears to offer advantages which have not previously been explored. The effect of the combination has been shown in the film, but is, I think, even more strikingly seen in the actual reproduction on an oscillograph which I have had the pleasure of witnessing in the authors' laboratory. Apart from its application to television, the paper contains a great wealth of valuable information on general circuit practice and, in particular, on the practice of cathode-ray oscillography. In this respect I would refer to the method of developing the line-scanning voltage, where the use of two hard valves instead of a thyratron is particularly elegant and obviates the difficulties that are commonly experienced in gas-discharge triodes at higher frequencies. The operation of the timing circuit in relation to the picture-framing frequency is fairly simple, but the relation of this timing circuit to the line-scanning source is less obvious and might, I think, be further elucidated by the authors. The operation of the chaser circuit might also be described in more detail. An interesting feature of the timing circuit is the readiness with which a saw-tooth generator of the type described can be locked to a sub-multiple of an applied frequency such as the 50-cycle mains. This may well prove a very valuable feature in the use of the 50-cycle mains as a control of picture presentation at the rate of 25 per second. The development of "hard" tubes, mentioned by the authors, is a matter of considerable interest, and the commercial production of such tubes will be welcomed by an increasing public of oscillograph users.

Mr. A. D. Blumlein: The authors, in referring to the mixture of signals sent to the radio transmitter, state that the absolute position of the spot may be transmitted as shown in Fig. 2(*b*). The differential of this curve will represent the intensity. As they point out, if the curve of Fig. 2(*b*) is transmitted the high-frequency components of intensity are very heavily attenuated. Transmitting in terms of intensities, this difficulty is avoided by using such a wave-form as that shown in the curve of Fig. 2(*c*). On the other hand, when this is done, some of the exactness associated with the transmission of the synchronization is lost. The difficulty may be expressed thus: in order to synchronize we wish to transmit the absolute position; in order to show varying brightness we wish to transmit intensities. If we transmit the absolute position we are transmitting the integral of intensity, and differentiation at the receiver increases the background noise enormously. If, on the other hand, we transmit intensity, we must integrate at the receiver to obtain the position. This latter arrangement would be satisfactory as regards background noise, but difficulties would arise owing to short severe interference which produces rectified pulses. If the intensity curve of Fig. 2(*c*) be transmitted and integrated to obtain position, one rectifying pulse of interference will displace the whole picture. Fig. 2(*d*) shows that the authors avoid some of these difficulties by mixing, and I should like to ask them the amount of mixture (time-constant) which they consider desirable. Even here difficulties appear to arise, since if differentiation at the receiver over the whole upper frequency-range is to be avoided, the time-constant at the receiver will be equal to the average line period, and interference causing rectification will displace a whole line. If a smaller time-constant be adopted to reduce the persistence of spot displacement, the high-frequency background noise will be increased. Another difficulty is that if a large component of intensity be transmitted it is necessary to transmit a large "downward kick" for the return stroke, as shown in Figs. 2(*c*) and 2(*d*), and this kick absorbs much useful space on the transmitter characteristic. Have the authors any circuit arrangement which will obviate having to transmit this back kick? The authors' reference to a scanning tube presumably applies to a tube such as that described recently in a paper by Zworykin.* Apparently when such a tube is used for velocity modulation it is necessary to couple the tube to the scanning mechanism so that the output of the scanning tube will always be zero. This is in effect a negative feed-back system holding the scanning-tube output to zero, its operation being such that the beam always restores charge to the discharged mosaic at a constant rate, thus giving correct velocity modulation. The difficulty here is that an amplifier in a high negative feed-back circuit shifts in gain as it cuts off; i.e. if the amplifier has any delay whatsoever the system will probably oscillate at a frequency dependent on the delay. Nyquist† has suggested a method of avoiding this general difficulty of negative feed-back amplifiers, but, even if this system is operable to prevent oscillation, I feel that the difficulty of obtaining a short enough delay practically precludes the use of the Zworykin type of scanning tube for velocity modulation.

Mr. H. M. Dowsett: In velocity modulation it is to be expected that the apparent size of the scanning spot will become smaller as its speed is increased. This change is clearly shown in Fig. 16; the scanning lines are indistinguishable in the white part of the picture where the spot velocity is less, but in the slightly shaded parts where the speed is higher they narrow down and show the unmodulated background as black lines. These background lines contribute more to the total modulation effect in the slightly shaded parts of the picture than does the modulation in the scanning lines themselves. The modulation is therefore obtained in three ways: (*a*) Varying velocity. (*b*) Varying size of spot. (*c*) Varying intensity. The resultant effect is remarkably good, having regard to the fact that there are three variables, although each becomes most effective at a different grade of modulation. One would expect that faithful reproduction would be more difficult to obtain than with intensity modulation applied as the sole method. The line effect, which is hardly noticeable in multi-line intensity modulation, may always be apparent in velocity modulation. Applying part of the modulation at the receiver may economize frequencies in transmission, but it prevents the quality of the total modulation at the receiver being checked by the monitor at the transmitter.

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* *Journal I.E.E.*, 1933, vol. 73, p. 437.

† British Patent Specification No. 374130.

Major A. G. Church: My interest in the development of television is general rather than technical. I am anxious to see intensive experimental research carried out by all commercial firms and research institutions in this country which are interested in the subject. For this reason I continually pressed the possibility of cathode-ray television both when I was a member of the House of Commons and later when I became a director of companies here and abroad engaged in the manufacture of television apparatus. I have become acquainted with the work of the leading exponents of television in Germany, and my many long conversations with von Ardenne during the past few years have familiarized me with the attempts that he has made to overcome the inherent difficulties of producing a satisfactory image on the end of a cathode-ray tube. I do not share the authors' pessimism with regard to the direct television of subject matter from the place of origin. I think that this is not only possible but practicable, and that results will soon be obtained at least equivalent to, and probably better than, those shown in the authors' film. The question which emerges from the paper is: Why use velocity modulation plus intensity modulation when we could rely on intensity modulation alone? Are the authors convinced that velocity modulation, as such, is not the ultimate solution of television from the point of view of reception? As regards the transmitter, as yet it is impossible to say whether a system such as that of Zworykin is practicable or necessary. I agree with the authors that it is impossible to combine velocity modulation with a mechanical method of transmission. If the latter is adopted we have to fall back upon intensity modulation at the receiver. There is no difficulty in producing a satisfactory cathode-ray image at the receiver by means of a mechanical form of transmission, and I am far from convinced that mechanical transmission with intensity modulation at the receiver will not finally hold the field. The authors' and other researches are indicating great possibilities in the field of applied physics; for example, ultra-short waves. Such researches are resulting in the improvement of photo-electric cells, cathode-ray tubes, synchronizing devices, scanning methods, optical systems, and studio technique, and are giving rise to new electric circuits. In my opinion the amplifiers used in the authors' receiver are too complicated and involve too many valves. I should like to ask whether the pictures shown in the film were received over a radio link; if so, was there any difficulty in regard to electrical interference? Also, what voltages did the authors use at the transmitter and the receiver? I should like to emphasize that there are any number of fascinating problems awaiting solution in connection with scanning devices, particularly in regard to mechanical methods of scanning.

Mr. C. O. Browne: The success of velocity modulation seems to me to depend to a large degree upon the question whether the concentration of detail into the bright portions of the picture at the expense of that in the dark is a favourable feature. I am inclined to submit that it is not completely so, and that it would be better to have the same amount of detail in the dark parts of the picture as in the bright. Suppose that we take an object which reflects light more from some parts of its surface than others; if we subject this object to varying amounts of illumination the ratio of the amount of light reflected from the bright parts of the object to that reflected from the dark parts will be the same, independent of the strength of illumination. It seems to me, therefore, that the changes in illumination, and also the detail, at all parts of the picture are likely to be the same irrespective of whether we are considering a portion which is strongly illuminated or one which is weakly illuminated. The only point which supports the concentration of detail in the light parts of the picture lies in the fact that the eye can appreciate detail much more readily when the detail is situated in a field of strong intensity than when it is situated in a field of weak intensity. For instance, we automatically take an object which we want to examine more minutely to the window, where the intensity is comparatively strong. This, however, seems to me to be no argument that, because the eye does not so readily appreciate detail in a weakly illuminated field, a television system should be allowed to render the detail in the dark portions of the picture even more obscure. This requires special emphasis when, as is often the case, especially with outdoor scenes, the bright areas do not necessarily contain the centre of attraction.

Mr. J. C. Wilson: With orthodox intensity-modulation it is always possible, and with normal channel-widths it is also practicable, to correct up to a point for the effect of the finite aperture size; such correction materially enhances the definition and limiting resolving-power of the system, and adds to the artistic value of the picture. I have myself observed transverse lines one-twentieth of the aperture-length in thickness and less than an aperture-length apart to be resolved by a low-grade system using amplitude equalization for the effect of transmitting and receiving apertures. I think the authors' demonstrated results would be susceptible of improvement in an analogous manner were it not for the fact that an analysis of the equation of motion of the scanning spot for perfect reproduction, when the effect of the finite spot-size is taken into account, shows that the signal increases in complexity in the sense that the higher-frequency Fourier components become increasingly important constituents as the size of the element approaches wavelengths of the shade-distribution. This is so, of course, for an intensity-modulation system also, but whereas in this case the distortion factor contains, for a round aperture, a Bessel function of the first order,* in the case of velocity modulation successive Fourier terms have as coefficients Bessel functions of progressively increasing order† (which have the property of remaining small until the argument approaches a value numerically equal to the order), and the adequate correction for this distortion almost baffles the imagination. My second point concerns the frequency ranges necessary for the transmission of equal amounts of intelligence by the two systems. I originally[*] held the view that with velocity modulation the signal might more fully utilize an available channel-width than with intensity modulation, which yields a kind of "line spectrum" with gaps between energy-concentrations. Dr. Hudec holds the opposite view,[†] however, in spite of the fact that if, following von Ardenne, the positional component of the velocity-modulation signal is suppressed, the Fourier series representing many simple shade-distributions appear to converge more rapidly in the case of velocity modulation than in that of intensity modulation. No doubt the difficulties of arriving at a theoretical estimate of the band width necessary for a specific degree of fidelity in the reproduction are still further increased by the admixture of an unspecifiable amount of intensification: but on this matter the authors will be able to speak from actual experience.

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* *Bell System Technical Journal*, 1927, vol. 6, p. 600.

† This analysis is treated more fully in a paper which was read by Mr. E. E. Wright before the Physical Society on the 20th April, 1934.

Mr. W. F. Tedham: Since the whole system is interesting as an attempt to apply the velocity-modulation principle, I should like to know whether the authors considered designing special valves to follow more accurately the hyperbola associated with correct tone-rendering. The question of flicker is worth attention. The number of flickers per second with which the film is projected has a great effect on the quality of the result. I should like to ask the authors whether the film during the demonstration was obturated twice per frame at 24 frames per second, or whether we were observing actual television conditions for flicker. On a full velocity-modulation system the frame frequency is proportional to the reciprocal of the picture brightness. Hence the frame frequency is smaller where the pictures are brighter —a fact which results in excessive flicker of bright pictures. Similarly there will be excessive flicker of bright places on the pictures.

Mr. N. M. Rust: In connection with the photo-cell amplifier, the application of the paraphase principle to the elimination of troubles due to intercoupling is very interesting. The authors mention that they found it necessary to reduce the time-constants of the grid coupling circuits of the last two valves of this amplifier. It would be interesting to know why and how the paraphase system failed when the lower limit to which it was possible to make the frequency-response flat was reached. Was the failure due to lack of balance in the valve circuits, to non-linearity in the characteristics, or just to lack of screening? The cathode bias resistances are shown in Fig. 5 as not being decoupled. In the formula on page 71, which gives the amplification of the circuit, no allowance is made for the anti-coupling effect due to this. To eliminate distortion, it is a good thing to avoid using decoupling condensers, but when a high-gain amplifier is necessary this is not always possible. In connection with the diminutions of response of the extreme low and high frequencies which occur stage by stage, we have found it better to compensate for such losses stage by stage, rather than by a lump correction. The formula at the bottom of the first column on page 74, in which the coupling efficiency is expressed in terms of the time-constant of the coupling circuit and the frequency, makes this clear. The expression for the overall efficiency of four stages, for instance, would involve functions of the frequency of the second, third, and fourth power, as well as the main term involving a direct function of the frequency. For low frequencies the second-order and third-order terms become quite appreciable in comparison with the main terms, and therefore a simple correction network will not give satisfactory compensation.

Dr. L. E. C. Hughes: The transmission of a complex signal not only requires equalization of attenuation and linearization of phase retardation, but it is also necessary that the phase intercept should be made a multiple of 2π; odd multiples of π are easily accommodated by reversing the legs of the circuit. Fig. A shows the necessary curves. If the measured attenuation of a circuit is α, then, theoretically, a component having the attenuation curve α' can be added in any part of the circuit, subject to noise-level limitations, so as to make the overall attenuation of the system (curve α'') constant. In practice, smooth variations in α can be readily equalized, as shown by the authors, but irregularities cannot be smoothed out in this way to give the desired uniform α''. Likewise the phase retardation of the system can be measured, and denoted by the curve β. Within limits, phase-compensating networks, of phase retardation β', can be introduced into the circuit to make the phase-retardation/frequency curve straight (e.g. curve β''). The slope of this curve is proportional to the delay in the transmission of the signal; a different delay in the transmission of the signal is obtained with networks of different phase-retardation, as in curve β' (dotted), but the required linearization is obtained in the same way, as shown in curve β'' (dotted). Whatever the delay in the transmission of the signal, it cannot be received undistorted unless the phase intercept β (i.e. β'' at $f = 0$) is an exact multiple of 2π. The reason for this, and a method for making it so when the phase intercept is not a multiple of 2π, will shortly be published by A. T. Starr. The practical question is how far these theoretical criteria for perfect transmission of signals

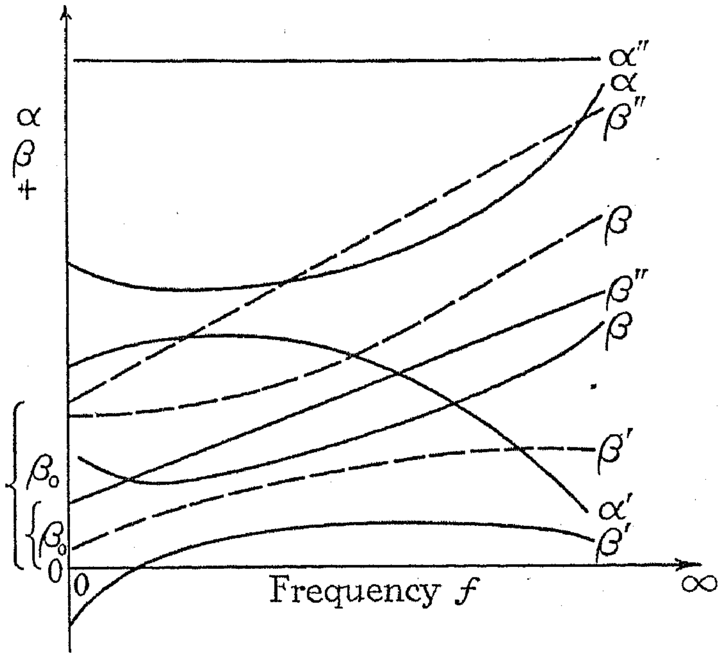

FIG. A.

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[*] *Journal of the Television Society*, 1933, vol. 1, p. 268.

[†] *Elektrische Nachrichten-Technik*, 1932, vol. 9, p. 213.

must be adhered to. In all forms of reproduction—visual, telegraphic, or acoustic—this is a matter for trial, and the only safe procedure is to establish transmission circuits which do adhere to the complete criteria for transmitting perfect signals, and then determine, by introducing known degrees of distortion, the extent to which it is commercially justifiable to employ refinements to eliminate them. The principle is that one cannot guess what is lacking when the known criteria are not complied with. The higher the grade of overall transmission, the more important this principle becomes. An analogous point of interest is the flexible intensity-control introduced by the authors. This is strictly parallel to the constant γ required in all photography, and particularly in sound-recording on film. For correct registration of the luminosities of an object on a photographic film, the value of γ obtained by development should be unity. Likewise on printing, the positive must be developed to a unity value of γ if the luminosities in the negative are to be faithfully reproduced. It can be shown that the same overall result is obtained if the product of the values of γ in the negative and the positive is adjusted to unity, apart from their individual values. In the variable-density system of photographic sound-recording, this criterion is critical. In pictorial work, reproduction in black and white robs the eye of much contrast because of the elimination of colour. In cinematographic work, the product of the gammas is therefore taken up to 1·3 or 1·4, or even 1·8 in sub-standard film, to compensate for this effect. Visual scanning of black-and-white positive film requires the overall value of γ to be unity in a television system, because the film has already its correct contrast. Scanning normal images necessitates an increase in contrast because of lack of colour. Some television systems use excessive contrast. The authors' system has a degree of artistic flexibility in variable contrast in the receiver and under the control of the user. This is in parallel with volume-control and tone-control in acoustic reproduction. For perfect visual and aural reproducing systems it is true that flexible controls in the hands of the recipient are erroneous in principle, but in the present state of commercial technique it is desirable to take the artistic finishing touches out of the hands of the designer and place them in the hands of the recipient, by providing him with suitable controls. As indicated in a previous discussion,* I am in agreement with the present authors that programme material for television will use standard film as a medium. An audience which is not interested in technique, however small it may be, does not tolerate screen images unless they are edited, and this process takes time. Editing can only be developed for particular systems of transmission when the material is recorded, i.e. on steel tape for broadcasting, or on film, both sound and scene, for television.

Dr. A. E. Martin: Consider the pure velocity-modulation system, and suppose that we are scanning a film or picture which is almost uniformly dark. The spot will move with almost uniform velocity, both at the transmitter and at the receiver. Similarly, the scanning of a nearly uniformly bright subject will cause the spot to move almost uniformly at both receiver and transmitter. It will be the same spot, of constant intensity, whichever picture it is scanning, and the area scanned will be the same: therefore, apparently there is no difference in intensity at the receiver between the almost entirely dark picture and the almost entirely bright picture. I should like to know whether there is a fallacy in this argument. I agree with Major Church that the possibilities of mechanical scanning are not yet exhausted. It is, at any rate, more suited to wireless transmission over the ordinary broadcast band. The cathode-ray methods described by the authors demand side-bands up to 200 kilocycles per sec., which are quite out of the question so far as the ordinary broadcast wave-band is concerned. The ordinary Baird television broadcast system can operate with side-bands which are alleged to be no wider than 10 kilocycles per sec. The difference between this figure and 200 kilocycles per sec. seems to me far greater than the difference in detail between a good Baird televized picture and the cathode-ray picture. The mechanical method may possibly displace the cathode-ray tube, even at the receiver, because if it can be made to operate successfully at the transmitter it should work equally well at the receiver. It affords the possibility of projection over a large area, which the cathode-ray tube does not, unless the screen material is greatly improved as regards brilliance.

Mr. R. Mines: I notice that transformers do not appear in certain of the authors' circuit diagrams. With some engineers audio-frequency transformers were not popular; but they were used more when their frequency-response characteristics were suitably improved. The requirements of television are very much more exacting than those of radio-telephony, and, furthermore, interference limitations cannot be overcome by such improvements to the characteristics of transformers. There is mentioned on page 81 the fact that the signal/noise ratio is one of the limitations to improving definition in a television system. It is common knowledge that the signal/noise ratio is a limitation where it occurs on the radio link between the transmitter and the receiver; the point brought out in the paper is that it is a limitation also where it occurs in the photo-cell amplifier. Have the authors compared the complexity and cost of a system such as theirs, employing velocity-modulation primarily, with that of the earlier systems relying primarily upon intensity modulation? A glance at the diagrams in the paper suggests that the velocity-modulation system involves greatly increased complexity and elaboration. Is "paraphase" a technical term for what is often described as "push-pull"? The word "paraphase" is applied in the paper to resistance-capacitance coupling, whereas we associate push-pull with transformer coupling. Is this the only difference between them?

Mr. P. W. Willans: The authors have presented their paper at a most opportune moment in the development of television, since if the broadcasting of television programmes is to become a commercial service it is necessary at the outset to make a choice of the manner of transmitting. I am inclined to the view that the difficulties of synchronization in television are overstressed by the authors, and that the advantages which their system gives in freedom from such difficulties are somewhat illusory. If two systems, at the transmitter and the receiver, are naturally isochronous, they will run exactly together and will never vary in phase. Once the correct phase relation has been obtained no control is necessary. In view of the fact that it is possible to approximate to natural isochronism, the production of precise synchronization seems to require the transmission of very little intelligence. My experience is that synchronized cathode-ray systems work admirably; many sets of this type were on view at the German Radio Exhibition of last year, and in no case was any irregularity noticeable. The criterion of the possibilities of velocity-modulated television lies in the results obtained and in the all-important question of the cost of receivers. Great interest will attach to the question of the way in which the apparatus is affected by external interference, particularly that due to passing motor-cars. This type of interference may possibly be reduced by the compulsory connection of resistances in series with the sparking plugs, but at the present moment it is a formidable factor and it is vital to know whether it will have more or less effect on the authors' apparatus than on systems of the intensity-modulated type. I gather that the authors have not yet any information to give us on this point. Turning to the question of cost, the real possibilities of the authors' system seems to lie in the ability to operate with cheaper tubes and lower H.T. potentials. If the authors are able to produce results equal to those shown in their film, with a tube not very different from those of the normal gasfilled type and with H.T. potentials materially lower than the 5 000 to 10 000 volts which the intensity system seems to require, there are ample arguments to be advanced in favour of their system. On the other hand, if it is subject to the handicap of being unable to be used for the scanning of real-life objects ("flying spot" scanning being impossible), then the argument goes the other way; although the production of an intermediate film for immediate retransmission may prove to be the most satisfactory solution for all types of television broadcast. I feel very strongly that something substantially the equivalent of real-life broadcasting will be necessary, just as in the case of sound broadcasting, where the listening public exhibit an unmistakable preference for real artists as distinct from gramophone records.

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* *Journal I.E.E.*, 1931–32, vol. 70, p. 351.

(*Communicated*) I am uneasy about the authors' compromise in adopting implicit synchronism for line scanning and explicit synchronism for picture traversing. It appears to be a necessary consequence of this method of operation that the picture should be traversed by means of a ratchet circuit such as that described, and the ingenuity of the devices adopted for this purpose are of no avail if, as I am inclined to fear, the result is that interference "gets into" the picture-traversing system and operates the ratchet. The effect, if this took place, would be that scanning lines would be missed out and large blank spaces left in the picture every time a motor-car came within range of the apparatus. The virtue of a synchronized system is that, by the sacrifice of a certain time-interval in the back stroke at the end of each line, a synchronizing signal can be sent out which is distinguishable from the extremely short pulses characteristic of motor-car interference by comparatively slow growth and decay, as also by the moment of its incidence. The authors' ratchet must necessarily be operable by a signal of very short duration (otherwise the back stroke would be visible) and, from the nature of velocity modulation, at any moment of time. It therefore appears extremely liable to be operated by interfering pulses of short duration, which are all too common on the available wavelengths. I shall await further information from the authors on this point with interest, and in hope that my surmise may prove to be wrong. Had the authors employed two channels in the manner of von Ardenne, or according to any other alternative, their position as regards interference would have been entirely different. The effect of an impulse of very short duration would have been to remove the spot from the screen at very high speed and to restore it again. The effect would thus be scarcely noticeable, and might give a marked advantage over intensity-modulation systems, where over-modulation by an interfering impulse results in a large "blotch," owing to the spot going out of focus. If it were found that substantially all interference on ultra-short waves consisted of very short impulses, a 2-channel velocity-modulation system might thus automatically yield a high degree of immunity.

Mr. D. C. Birkinshaw: I should like to ask the authors to explain more fully their estimate of 240 kilocycles per sec. for the frequency band required. I imagine that they are operating with about 150 scanning lines, and, basing my estimate on the method of calculation used in an intensity-modulation system, I consider that this would necessitate 375 kilocycles per sec. when working up to half the critical frequency (i.e. equalizing the detail in both directions) or 750 kilocycles per sec. when working up to the first critical frequency (i.e. taking full advantage of aperture correction). If the amount of intelligence transmitted on the velocity-modulation system is the same as that transmitted on an intensity-modulation system having the same parameters, presumably the same frequency band is required.

Mr. K. S. Davies: In Figs. 16 and 17, and also in some of the films shown by the authors, I notice that the reproduced picture is not truly rectangular, presumably through the use of unbalanced electrostatic deflection in the oscillograph tubes. If this is so, I should like to know whether the authors have considered obviating the effect either by the use of push-pull deflection on both pairs of plates or by using magnetic deflection.

Mr. D. G. Reid: With regard to the time-lag and phase-shift curves given by the authors in the lower portion of Fig. 8, it is usually understood that the delay which a signal experiences in passing through any network is proportional to the slope of the phase-shift/frequency curve; in certain parts of the frequency range in curve B this is shown to be negative. This presumably means that the signal comes out of the amplifier before it goes in! Also, no scale is given for the dotted time-delay curve A, and I should like to know the method by which it is derived, since the time-delay appears to be substantially constant over frequency ranges where the slope of the phase-shift curve is changing considerably.

Mr. W. E. Benham (*communicated*): The authors have achieved results of entertainment value with a television system which has been considered by many to present almost insuperable difficulties. The extremely neat solution given for the form of operator required to compensate for finite time of screen after-glow, and its realization in practice, appeal to me more than anything else in the paper. Indeed, my only criticism of paragraph (4·141) is that no attempt is made to include in the treatment the effect of finite spot size and variable velocity scanning. When this is done for the case of a spot scanning the screen and throwing an image on to a film with transparency η, the light on the photo-cell at a time t after an abrupt transition in η cannot be compensated for afterglow-time for values of t comparable with T, the after-glow time-constant. If the spot be assumed square for simplicity, the following expression gives, for any size of spot, the light on the photo-cell at a time t after an abrupt transition in transparency from η_1 to η_2, t being measured from the instant the spot becomes entirely contained in the region η_2.

$$K'I\left\{\eta_2 + (\eta_1 - \eta_2)\left[\left(1-\frac{T}{t_s}\right) + \left(1+\frac{T}{t_s}\right)e^{-t_s/T}\right]e^{-t/T}\right\}$$

The new quantity entering into this expression is t_s, which represents the amount of time taken by a square spot to lap its own side. If we let t_s tend to zero, the expression readily yields that given by the authors on page 70 for an infinitely small scanning spot. We can achieve perfect compensation in the case of constant-velocity scanning, for then t_s is constant during the operation $(1 + TD)$, which simply leaves us with $K'I\eta_2$, as for an infinitely small spot. In velocity modulation, however, t_s will be continually changing, so that if we allow for this fact when operating with $(1 + TD)$ we obtain

$$K'I\left\{\eta_2 + (\eta_1 - \eta_2)\left[\frac{T^2}{t_s^2}(1 - e^{-t_s/T}) - \left(1 + \frac{T}{t_s}\right)e^{-t_s/T}\right]e^{-t/T}\frac{dt_s}{dt}\right\}$$

This expression can be simplified in cases where t_s/T is small compared with unity. We then have

$$K'I\left[\eta_2 - \frac{(\eta_1 - \eta_2)}{2}e^{-t/T}\frac{dt_s}{dt}\left(1 - \frac{4}{3}\frac{t_s}{T}\right)\right]$$

Taking T, t_s, and t, as 6, 1, and 6 microseconds respectively, and $\eta_1 = 100\eta_2$, we obtain

$$K'I\eta_2(1 - 14\cdot 1 dt_s/dt)$$

This shows that for comparatively slow transients ($dt_s/dt = -0\cdot 1$) we shall get more light due to η_1 than to η_2, even when the spot has travelled 6 spot-diameters into the region η_2. The effect will thus be noticeable when the scanning spot passes from a highly transparent to a relatively opaque area of film, and there will be a tendency for white to remain white for some distance in the black—for one direction of scanning only. Referring to Fig. 17, an effect of this sort is clearly noticeable all the way down the bandmaster's back, also down one side of the nearly vertical position of his sling belt. Clearly this defect will be very much reduced in the case of a screen with a still smaller after-glow time-constant, if this can be attained in practice.

Dr. L. Levy (*communicated*): As the visible image in the system of television devised by the authors is obtained by variations in the degree of illumination of a fluorescent screen, it is clear that the nature and quality of the fluorescent materials employed are of paramount importance. These fluorescent materials should fulfil certain desiderata, of which the following are the most important. (*a*) The intensity of fluorescence under a given cathode-ray bombardment should be as great as possible. (*b*) The colour of the fluorescent light is preferably approximately white. (*c*) The material should be of fine grain, so that it can readily be coated and the image produced is not granular in appearance. (*d*) The intensity of fluorescence should not suffer by reason of the actual bombardment. (*e*) The fluorescence should not be accompanied by phosphorescence, persisting after the removal of the exciting radiation. These desiderata taken in conjunction are not very easy to comply with in every respect. Generally speaking, the most intense fluorescent effects are obtained when the fluorescent material is in the form of relatively large crystals; grinding of these greatly impairs their fluorescence. The materials hitherto employed for the production of screens for cathode-ray oscillographs have been either a specially prepared willemite (synthetic zinc silicate), or calcium tungstate, or (occasionally) cadmium tungstate. The latter materials have until recently been the only substances employed for the manufacture of intensifying and fluoroscopic screens used for X-ray purposes. Recent research has led to the development of a new series of zinc and zinc-cadmium sulphides for the construction of X-ray screens. These materials are greatly superior to the tungstates formerly used, and they give a more intense illumination in cathode-ray tubes than any other substance so far employed. These materials fulfil the majority of the desiderata enumerated above, and it is quite certain that further research directed towards the production of materials specially designed for use in cathode-ray tubes will lead to the development of preparations suitable in every respect. The use of these materials will enable the size of the televized image to be increased without any reduction in the intensity of illumination.

Messrs. L. H. Bedford and **O. S. Puckle** (*in reply*): We wish to thank the various speakers who took part in the discussion, and in particular Messrs. Herd, Blumlein, and Benham, whose remarks are dealt with first in the reply as they appear to us to be of outstanding importance.

Mr. Herd points out that the description of the operation of the timing circuit in relation to line scanning might with advantage be elaborated. Perhaps the functioning of this arrangement can most easily be made clear by describing an earlier embodiment of the same idea. In the older arrangement there was no locker valve V_5 (Fig. 3) and the scanning was stopped by short-circuiting the resistance R_2 with a relay. When the relay contacts were closed the commencement of current in the trigger valve V_2 passed no pulse to the grid of V_3, hence no cumulative discharge was initiated, and the cathode of V_2 simply ran to a potential sufficiently negative to allow V_2 to pass an anode current equal to that of V_1. This condition persisted until the relay contacts opened, whereupon V_3 received its pulse and the normal discharge took place. It was found in practice that the adjustment of this relay was a matter of considerable difficulty and that the adjustment could not be held for sufficiently long periods. We were therefore forced to find an electrical equivalent for this mechanical device. (It may be said here that this experience was repeated on every occasion on which we used a mechanical arrangement at the transmitter, so that we have been led to the very definite conclusion that the use of mechanical devices is to be avoided.) With the above explanation the functioning of the electrical locking circuit shown in Fig. 3 should now be clear. When the valve V_5 receives a positive pulse on its grid, it functions in exactly the same way as would V_2 with the resistance R_2 short-circuited.

Mr. Herd refers to the use of 50-cycle mains for controlling the picture speed of 25 per sec. We wish to point out that, whilst agreeing entirely with his remarks, we think they are a little liable to misinterpretation in that they might be taken to suggest that the 50-cycle mains can be used for establishing picture synchronization at the receiver. We regard this practice as illegitimate.

Mr. Blumlein asks what we consider the most favourable ratio of displacement and velocity components in the " transmission mixture." In the case of reception free from outside interference, the limiting field strength receivable is determined by valve background noise at the receiver. To obtain the most favourable conditions in these circumstances, one would work with the highest possible proportion of velocity signal. On the other hand when there is local interference in the nature of sharp pulses occurring at moderately low frequencies it will be advantageous to work at the other extreme, namely a high proportion of displacement signal. It is a merit of the system that it allows a reasonably wide choice of the mixing ratio (time-constant), and a satisfactory value will have to be fixed by trial under average ether conditions. With regard to the large downward kick corresponding to the back stroke, it will be noticed that the displacement and velocity components are in opposition during this stroke, and the demand on carrier depth is therefore not so serious as might otherwise be expected.

With regard to the iconoscope, we disagree with Mr. Blumlein in his conclusion that this type of scanner cannot be adapted to velocity modulation. We have, of course, no direct experience of this instrument, but from what has been published on the subject we infer that it should be quite as suitable for velocity modulation as for any other method. The fact which Mr. Blumlein overlooks, and which leads us to the opposite conclusion, is that we do not use and do not want full velocity modulation—that is to say, scanning in which the spot velocity is inversely proportional to the local light intensity. We think it worth while to explain how we would propose to use a scanner of the iconoscope type in conjunction with velocity modulation. Suppose that we have an iconoscope whose output is coupled through an amplifier to the grid of a time-base charging valve such as V_1 in our drawings. Let the iconoscope yield a voltage v on the grid of the valve when the local light intensity is f and the instantaneous scanning velocity is u; these quantities will be related by the equation $v = kfu$, where k is a constant of the iconoscope with its associated amplifier. In Fig. B, let the anode-current/grid-voltage characteristic of the valve be drawn in the left-hand quadrant. The vertical scale can also serve as a scale of scanning velocity. In the right-hand quadrant we may plot a scale of local light intensity along the abscissa. Now for any point P on the valve characteristic we can calculate a value of the light f from the equation $f = v/(ku)$, and hence obtain a point P′ correlating the light value f and the scanning velocity u for the complete system. A succession of such points gives us the characteristic in the right-hand quadrant. It may be noted that it is now no longer necessary to use a variable-μ valve for the charging valve, as the property of the iconoscope itself—that the output current is proportional to the scanning velocity—shapes the lower part of the characteristic appropriately.

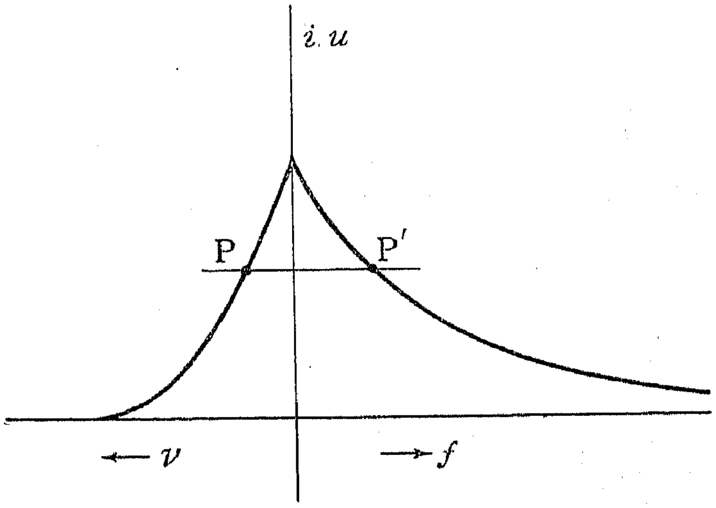

FIG. B.

Mr. Benham draws attention to a question of considerable importance, namely: Is it legitimate to consider after-glow and aperture effects separately, as we have done? He concludes that it is not legitimate, but we have to disagree with him on this point. We agree with his expression for the light on the photo-cell at time t after the end of a transition, but we do not agree with his deductions from it. For any time $t>0$ the quantity t_s must certainly be regarded as a constant in the expression, so that for such times the legitimacy of our assumption is established. Mr. Benham's expression is not valid for $t<0$, and hence no deduction can be made from it as to the state of affairs during the transition itself. Mr. Benham's expression dt_s/dt appears to us to be without meaning.

We will now establish more generally the independence of the after-glow and aperture effects. The difficulty of this matter resides particularly in finding a suitable point of view and expressing it in a good notation.

First of all, regarding the matter from a physical point of view, we may note that any light arising from portions of the screen which are not actually under bombardment is decaying exponentially with time-constant T, so that if F_1 is the total amount of this light as seen by the photocell at any instant $t = 0$, then at time t this light is $F_1 e^{-t/T}$. If we operate on this expression with $(1 + TD)$ we get precisely zero. Hence the effect of the operator is to annihilate the signal due to the decaying after-glow. According to our hypothesis as to the nature of the after-glow, however (see Section 4·141), the whole of the existing light, even in regions under bombardment, may be regarded as decaying with time-constant T, the total rate of decay of light being equal to the rate of formation of new light, kI, by the bombardment. The signal due to the decaying light is annihilated by the operator $(1 + TD)$; and the same operator, when applied to a light signal of zero value but having a uniform rate of increase kI, yields an effective light signal kIT or $k'I$. Hence the effect of the operator $(1 + TD)$ is to make matters appear as if we had a light response $k'I$ localized at the ray head and without after-glow.

It is, however, desirable to give a more rigorous mathematical proof of the last statement. Suppose that a spot of finite size passes over the screen, not necessarily at constant speed. If the process is started at time $t = 0$, we may reckon the light flux on the photocell at time t as

$$\int_0^t kIdt'\eta e^{-(t-t')/T}$$

In this integral η is the value of the transparency on which the spot falls at time t'. If there are variations of transparency within the spot, the value of η is to be obtained by averaging. In any case η is a function of t' and not of t.

We now have to inquire the result of operating on this integral with the operator $(1 + TD)$, where D means, in this notation, d/dt.

We have

$$\frac{d}{dt}\int_0^t kI\eta e^{-(t-t')/T}dt' = kI\eta_{(t)}e^0 + \int_0^t kI\eta \cdot \frac{-1}{T}e^{-(t-t')/T}dt'$$

Hence

$$(1 + TD)\int_0^t kI\eta e^{-(t-t')/T}dt'$$

$$= \int_0^t kI\eta e^{-(t-t')/T}dt' + kI\eta_{(t)} + \int_0^t - kI\eta e^{-(t-t')/T}dt'$$

$$= kI\eta_{(t)}T$$

$$= k'I\eta_{(t)}$$

which proves the statement.

Mr. Dowsett states that in velocity modulation it is to be expected that the apparent size of the scanning spot will become smaller as its speed is increased, but this is by no means always the case. A study of the theory and practice of the cathode-ray tube makes this evident. We disagree that the varying size of the spot can be in any sense a contributing factor to the modulation; it can only affect definition.

We think that further intimacy with the velocity-modulation system will convince Mr. Dowsett that instead of faithful reproduction being more difficult to obtain with our system than with the intensity-modulation system, actually the reverse is the case, since neither velocity nor intensity modulation is, at the present time, capable of giving entirely satisfactory results when applied independently, owing to lack of linearity in one case and excessive velocity requirements in the other.

In reply to Major Church, we are in no sense pessimistic with regard to direct television of subject matter from the place of origin; we merely fail to see that there is any possible advantage to be gained in 90 per cent of cases. We consider that direct subject transmission will have very little place in television in 5 years' time.

With regard to the value of combined velocity and intensity modulation, our views on the matter are embodied in the paper and in our answer to Mr. Dowsett. We are quite convinced that mechanical transmission will cease to have any appreciable share of the television field in a few years' time. We can see no reason whatever why it should be considered necessary or even advantageous to carry out a purely electrical job in a mechanical way, especially when such a method brings in so many extra difficulties which would not otherwise be encountered. For instance, with velocity modulation the synchronization problem is inherently solved, and this, as Major Church must be aware, is one of the outstanding difficulties of mechanical transmission.

While we do not consider the number of valves in our receiver to be prohibitive, we are of course using every endeavour to reduce the number, and have in fact already made some progress in this direction. It must, however, be remembered that our receiver does not have to provide two separate time-bases, each of them requiring to be synchronized, as is the case with cathode-ray reception by the intensity-modulation method.

Mr. Browne feels that it would be better to have the same amount of detail in the dark parts of the picture as in the bright; but surely he will admit that this is never so in practice. We submit that he would be most unusual if he could see detail as well in the dark corner of a room or in a dark object as he could in a light object, or in one which is brightly illuminated. The idea of concentrating the detail into the lighter portions of the picture is a well-known cinematographic principle, and it was, we believe, in an attempt to incorporate this principle in a television system that Thun, a cinematograph engineer, was led to the principle of velocity modulation. The increase in brilliance of the received picture due to the superposition of velocity and intensity modulation over that obtained with pure intensity modulation is a very startling one, and must be seen to be appreciated.

With regard to Mr. Wilson's remarks on the subject of aperture effect, it is certain that with mechanical transmission the aperture size is of great importance, for one must obtain a reasonable compromise between illumination of the subject and resultant spot size; but with our velocity-modulation system no aperture effect has been detected when working with definition corresponding to 180 lines. We have several reasons for coming to this conclusion, one of which is that when the scanning is slowed down (an operation carried out on our system by turning a knob) the definition can be made practically perfect. Perhaps Mr. Wilson noticed in our picture of Miss Amy Johnson that a single wisp of hair could be seen distinctly, and we think he will admit that there cannot be much aperture effect when such is the case, and that our results are not likely to be improved by aperture correction; the latter is in any case practically an impossibility with velocity modulation. The remedy is to reduce the size of the spot if trouble exists, and we have taken steps to do this.

With regard to the relative band widths required for transmission of a given intelligence by the velocity method and the intensity method, we think it will be clear that if the contrast level in the velocity-modulation case is kept extremely low, then the same frequency band is required for the same intrinsic detail in the two cases. If the contrast ratio in the velocity-modulation case is progressively increased, then it is necessary to raise the frequency band if the same detail is to be kept in the darker places. This, however, is not necessary, because a good compromise can be found for the same band width in which the increase of detail in the lighter places more than offsets the reduction in the darker places. This is true, however, only so long as the contrast level is kept fairly low. Further improvement in the contrast ratio can be obtained by intensification, which involves no increase whatever of the frequency band.

Replying to Mr. Tedham, we have not attempted to do much in the way of design of special apparatus for use with our system, preferring to make the system work with standard apparatus whenever possible. In any case a perfect hyperbola is not desirable as a characteristic for the charging valve, since we are using not a pure velocity-modulation system but one with intensification (see Fig. 15). The question of flicker is certainly worth attention. With regard to the film shown at the meeting, each picture was projected three times; but, in any case, the flicker could bear no relation to that actually obtained on the oscillograph, since cinema flicker and television flicker are of a totally different nature. When a full velocity-modulation system is employed the intrinsic frame frequency is proportional to the reciprocal of the picture brightness, but of course this would be quite an impossible condition to adopt in practice. We therefore run the film at a constant speed and ensure that the transmission of each frame takes the same time (see Section 4.13, last paragraph).

We are in agreement with Mr. Tedham's assumption that the flicker will be greater in the bright parts of a picture, but not for the reason which he gives. Since the repetition frequency is constant, the velocity modulation has nothing to do with the case. The reason for the increased flicker in the bright places is a physiological one.

Mr. Rust asks why, in view of the use of the paraphase system in the amplifier, it was necessary to reduce two of the coupling time-constants. We have not made a complete diagnosis of the mode of failure of the former, but it would appear that the very low frequencies associated with change of picture subject matter are incorrectly handled by the amplifier and give rise to a species of "bumping." There are also extraneous low-frequency disturbances due to mains fluctuations. The cathode biasing resistances in Fig. 7 do not require to be decoupled when the balance is accurately set, since these resistances carry only direct current.

We fully agree with Mr. Rust when he states that compensation for the various stage losses is better inserted stage by stage. A "lumped" compensation for more than one stage is usually only an approximation, and it is so in the one case in which we have used it. The lower end of the frequency characteristic A in Fig. 8 shows, however, that the approximation is a very close one down to the lowest wanted frequency of 25 cycles per sec.

Dr. Hughes's remarks regarding Starr's theorem are extremely interesting, but we feel that any reply should be deferred until the publication of the latter. We are also most interested in Dr. Hughes's remarks in which he compares the intensity control to a variation of the photographic γ. We are in entire agreement with his statement that an audience will not tolerate non-edited screen images, and we think Dr. Hughes is to be congratulated on being the first to point out this very strong argument in favour of film transmission.

Dr. Martin is perfectly correct in his statement that a pure white and a pure dark transmitted area, in each case covering the whole of the picture, would be received at equal intensities at the receiver; but the same applies to the intensity system and indeed to any system which does not embody the equivalent of d.c. transmission. It may be interesting to note that in the early stages of the development we did arrange for this d.c. transmission, but found it of no value.

Mr. Mines draws attention to the absence of transformers in our circuits. The use of transformers on the band width required for high-definition television pictures is quite out of the question at present, as no one has succeeded in making a transformer to cover such a wave band. This leads to the somewhat unfortunate result that whenever we need a transformer we have to use a valve instead; this accounts for two of the valves in our receiver. Had Mr. Mines seen our apparatus we feel he would not have complained about complexity and cost. Perhaps the circuits are rather more complex in conception, but that involves no extra difficulties in practice. The apparatus used consists almost entirely of valves, condensers, and resistances, all of which are cheap and easily obtained. With reference to the use of the word "paraphase," we thought this term was quite a normal one in the radio art. It is not at all the same as "push-pull," for in push-pull the grids are fed directly from the preceding stage, whereas in "paraphase" only one grid is fed from the preceding stage.

With regard to the remarks of Mr. Willans, we do not feel that we have over-stressed the difficulties of synchronization when using mechanical systems of transmission. When we visited the German Radio Exhibition in Berlin last August we took great trouble to find out how synchronization was being carried out in German television systems, and were informed that separate lines were being used for this purpose except in one case; in this instance the picture kept slipping out of synchronism. Since good synchronization was only obtained with the aid of separate lines, we infer that German television experts were not at that time so happy about the matter as is Mr. Willans. The velocity-modulation system, utilizing as it does a transmitted signal which in itself contains the spot displacement, must of necessity remain in perfect synchronism. Mr. Willans will agree that it is better to use a system which requires no synchronization rather than one which depends on "natural isochronism," which does not exist in nature. When the receiver embodies a mechanical scanning disc, matters are even worse, for at the slightest tendency to run out of phase an excessive amount of power has to be used to bring it back into proper synchronism, because of the inertia of the rotating mass.

With regard to interference to receivers caused by passing motor-cars, we are as yet unable to give any definite information. The question of cost is also not an easy one to settle, but our receiver should compare favourably in this respect with those of other systems. Turning to Mr. Willans's remarks on the subject of direct subject transmission, the demonstrations of the use of an intermediate film which we saw in Berlin were rather unsatisfactory, though possibly capable of development. We consider that Mr. Willans is not entirely justified in comparing television with sound broadcasting, when he says that the listening public exhibit "an unmistakable preference for real artists as distinct from gramophone records." A more suitable comparison would be between the theatre and the cinema, where, on account of the peculiar advantages associated with film technique, the public prefer pictures of artists to seeing the artists in real life.

As is explained at the beginning of the paper, it is not a necessary conclusion that the adoption of explicit synchronism for picture-traversing necessitates the use of a ratchet circuit. Moreover, the pulse operating the picture-traversing system is an extremely strong one, though of short duration, and any interference which could upset the picture-traversing would in any case be powerful enough to destroy the picture. Mr. Willans's description of the dire effects which would occur in such circumstances therefore need not worry us.

Replying to Mr. Birkinshaw, our estimate of 240 kilocycles per sec. was (as is explained in the paper) based on the assumption of 120 lines having 160 picture points per line (square elements) and 25 frames per sec. This results in a band width of $(120 \times 160 \times 25 \times \frac{1}{2})$ cycles per sec., or 240 kilocycles per sec. Actually, however, we have worked our system with numbers of lines varying from 40 to 200. We must repeat that with our system there is no need, and indeed it is practically impossible, to apply aperture correction.

The lack of rectangularity in Figs. 16 and 17 and in some of the films shown by us, pointed out by Mr. Davies, is due to the fact that the potentials applied to the front pair of deflecting plates modulate the sensitivity of the rear pair. We have already improved our tubes, and are now not seriously troubled with this effect. The use of magnetic deflection is rather objectionable on several grounds.

Mr. Reid raises a question with regard to the quantity which he calls the "time-lag" in the photo-cell amplifier. As explained on page 75, the curve designated "time-delay" in Fig. 8 represents the ratio of phase lag to angular frequency, and the curve was put in for the purpose of showing the linearity of phase displacement with frequency, which is not apparent from the other curves on account of the logarithmic frequency scale. Mr. Reid points out that the quantity usually accepted as the time-lag is not this ratio ϕ/p but the quantity $d\phi/dp$. The confusion is one of nomenclature, and may perhaps be cleared up by calling the quantity ϕ/p the phase time-delay, and the quantity $d\phi/dp$ the group time-delay.

We are extremely interested in Dr. Levy's remarks on the subject of cathode-ray screens, and are in entire agreement with him. We hope that the day is not far distant when a brilliant projected image of large size will be obtained from a cathode-ray tube, and when we shall be able to avoid the troubles which at present exist because of the presence of screen after-glow and light "spill over."

A RÉSUMÉ OF RECENT WORK ON THE ANOMALOUS BEHAVIOUR OF DIELECTRIC LIQUIDS.*

By W. Jackson, M.Sc., Associate Member.

(*Paper first received* 16*th October*, 1933, *and in final form*, 17*th April*, 1934.)

Summary.

The paper deals with the phenomena associated with the application of direct and alternating voltages to dielectric liquids. The possible explanations of the anomalous conduction-current and absorption-current components under continuous stress, and of the power loss in alternating fields, exhibited by such media, are discussed in terms of the evidences of recent research investigations.

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Introduction.

The behaviour of insulating materials under electric stress is a matter of fundamental and increasing importance to electrical engineers, and the need for a thorough investigation of the factors responsible for the limitations and uncertainties of commercial dielectrics was stressed in 1926 by Dr. L. Hartshorn.† This call has been answered by a concerted attack on the subject of dielectric phenomena by engineers, physicists, and chemists, of many countries during the past few years.

The important insulating properties of dielectric materials are (1) resistivity, or conductivity; (2) power loss in alternating electric fields; (3) electric strength. Each of these aspects of dielectric behaviour has received attention during recent years in a large number of scattered investigations covering a very wide field, and these have been productive of a marked increase of knowledge compared with that available at the time of the above-mentioned résumé. The present paper has been prepared, therefore, rather as a supplementary one to that of Dr. Hartshorn, with a view to bringing the conclusions which it was possible to draw in 1926 into line with the evidences of these more recent investigations.

In a single paper it is not possible, however, adequately to deal with all of the three aspects of the problem of dielectric performance mentioned above. No reference has been made, therefore, to the question of the electric strength of insulating materials, and of the phenomena which immediately precede dielectric breakdown under excessive voltage. It seems likely that the ultimate explanation of these phenomena can result only from a complete understanding of the anomalous properties exhibited by dielectric media when subject to more normal values of steady and alternating electric stress. The most important of these properties is the power loss occurring in alternating fields, but of a more fundamental nature are the phenomena of absorption and anomalous conductivity evident in studies under constant applied voltage. Much of the work of recent years has been concentrated on the elucidation and correlation of these anomalies, and it is with the results of this work that the present paper is concerned.

The paper has been limited to a discussion of liquid dielectrics, in particular to those of engineering interest. In this category may be included those materials which, while apparently solid at normal temperatures, continue with decreasing temperature to exhibit the characteristics of the highly viscous fluids from which they result.

Part 1.—BEHAVIOUR OF DIELECTRIC MEDIA UNDER CONSTANT APPLIED VOLTAGE.

(A) General.

According to the classical theory, the behaviour of dielectric media is specified by two quantities, the dielectric constant κ and the conductivity σ. When a constant voltage is applied suddenly to a condenser with such a dielectric, the current flow consists of two components: (1) the normal charging current, the magnitude and duration of which can be calculated from a knowledge of the resistance and inductance of the connecting leads and of the condenser capacitance, and which, in practice, falls rapidly to zero; (2) the constant leakage or normal conduction current, which persists so long as the voltage is applied. If now the voltage is removed and the condenser simultaneously short-circuited, the normal conduction current ceases, but the stored energy of the normal charging current is released as a normal discharge current of identical time variation but opposite sign.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications, except those from abroad, should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Bibliography, (1).

In practice, however, the behaviour of dielectric materials is more complex. This is evidenced by the presence of superposed anomalous charge and discharge currents, the decrease of both of which with time may continue for a long period after the normal charge and discharge currents have ceased to flow.

Although the normal charging current, corresponding to the production of a certain electric displacement in the dielectric, is perfectly reversible in the normal discharge current, no such generalized statement applies to the anomalous charging current. In some cases, particularly with liquid dielectrics, the anomalous discharge current is not comparable in magnitude with the corresponding anomalous charging current. It is therefore necessary to regard this latter current as composed of two components: (i) an irreversible component, corresponding to an anomalous conduction through the dielectric medium; (ii) a reversible component, corresponding to an anomalous displacement in the dielectric, and referred to as the " absorption " current. Neither of these phenomena, particularly the former, is yet completely understood. Their relative magnitude is dependent on the nature of the dielectric medium concerned.

Following Dr. Hartshorn, the current $I_c(t)$ entering the dielectric medium under constant applied voltage may be represented in its most general form as the sum of four components, namely the normal charging current $i_1(t)$, the normal conduction current i_2, the anomalous conduction current $i_3(t)$, and the anomalous charging current or absorption current, $i_4(t)$. Thus

$$I_c(t) = i_1(t) + i_2 + i_3(t) + i_4(t)$$

When the charged medium is short-circuited, the liberation of accumulated charge will be productive of a current $I_d(t)$ consisting of two components, namely the normal discharge current $i_1(t)$, and the reversible absorption current $i_4(t)$. Thus

$$I_d(t) = -\left[i_1(t) + i_4(t)\right]$$

It has been mentioned that the normal charge and discharge currents can be calculated. In any case they are, in practice, of such short duration that they may be regarded as having ceased to flow immediately the charge and discharge circuits are closed. If, therefore, records of charge and discharge currents be taken commencing respectively at the instants of application of and removal of constant applied voltage, and concluding when the current reaches a constant or zero value, the other current components can be separated at once. The reversible absorption current is given directly by the discharge curve on short-circuit of the charged dielectric medium; and the irreversible anomalous conduction current, added to the steady conduction current, is given by the difference between the corresponding ordinates for charge and discharge.

The apparent d.c. conductivity inferred from the steady-current value will depend, however, on the test conditions of voltage, electrode arrangement, and electrode separation, so that this current cannot be interpreted directly as giving a measure of a certain characteristic conductivity of the material in question.

The phenomenon of dielectric absorption is not so conspicuously a characteristic of liquid as of solid dielectrics. In many cases it is apparently absent. It is frequently noticeable, however, in highly viscous liquids, but whether it partakes fundamentally of the same form in such media as in solids is not yet clear.

The behaviour of liquid media under steady voltage is characterized mainly by their anomalous conductivity. On the sudden application of constant voltage the current has a high initial value, which decreases more or less rapidly with time, and in some cases many hours may elapse before a sensibly constant value is attained. The form of the current/time curve is somewhat similar to that characteristic of dielectric absorption in solids, although the absence of a discharge-current curve of corresponding magnitude indicates that the phenomena responsible for the current decay are of an essentially different character and origin.

(B) Sources and Nature of Charge Carriers.

The passage of electricity through insulating liquids has long been recognized as ionic in character. The source and nature of the current carriers, on which rests the performance of the media under electric stress, remain, however, matters of uncertainty, particularly in the case of the insulating oils of engineering practice.

(a) *Highly Purified Simple Liquids.*

During recent years much attention has been devoted, mainly by Nikuradse, to a study of the behaviour of highly purified simple liquids under constant voltage in the steady conducting state. From this, much additional evidence has emerged to suggest that the conduction through such media obeys the same laws as hold for gases. Nikuradse* has shown that the current/voltage curve relating to the residual conducting state for highly purified hexane and chlorbenzene exhibits a marked saturation region (Fig. 1), and is of essentially the same form as that obtained for gaseous media. At low values of the field strength Ohm's law is obeyed, but as the applied voltage is continuously increased the current begins to increase less than proportionally and then reaches a saturation value. This state of current saturation occurs when the rate of removal of the charge carriers by discharge at the electrodes is equal to the rate of production of new ions. Beyond this saturation region the current increases rapidly with rise in voltage, owing to a rapid increase in the number of charge carriers as the result of ionization of the liquid molecules by their collision with swiftly-moving ions. Under excessive voltage, breakdown of the medium results. The behaviour discussed in the present paper does not relate to this third region of the current/voltage characteristic.

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* See Bibliography, (2).

From this similarity it is to be expected that a volume ionization in highly purified liquids can arise from the same external agencies as are productive of gaseous ionization. This is supported by the fact that such agents as γ-rays and X-rays are known to produce a marked increase in conductivity.* In practice, however, the effect of natural radio-active influences is small compared with those arising from other sources, even in the case of very pure liquids.

Nikuradse regards the conduction in the regions (1) and (2) of the d.c. current/voltage characteristic of Fig. 1 as arising from spontaneous ionization of liquid molecules at the electrode surfaces.† This postulation of surface, as opposed to volume, ionization is based on the fact that the current was found to be sensibly independent of the electrode spacing. Actually in the cases of purified hexane, benzene, and chlorbenzene, the presence of a weak volume ionization was indicated by a slight increase in saturation current with spacing. If it had been a question of pure volume ionization, the (saturation current)/(plate separation) curve would have been a straight line through the origin. Nikuradse explains the occurrence of surface ionization and of saturation in terms of the inequality $\phi_+ \gtrless \phi_-$, where ϕ_+ is the exit work of an electron leaving the metal and ϕ_- the energy freed when an electron is brought from a vacuum into the liquid medium. If ϕ_+ is less than ϕ_- a voluntary exit of electrons from the metal is postulated, until a state of equilibrium is imposed by the field set up between the metal and the proximate liquid sheet by the liberated electrons. The magnitude of this contact potential depends on the nature of both the metal and the liquid. In the conducting process the liberated electrons are associated with the liquid molecules to form ions of relatively low mobility. Current saturation results when the applied voltage becomes sufficient to transfer the liberated electrons as fast as they are produced.

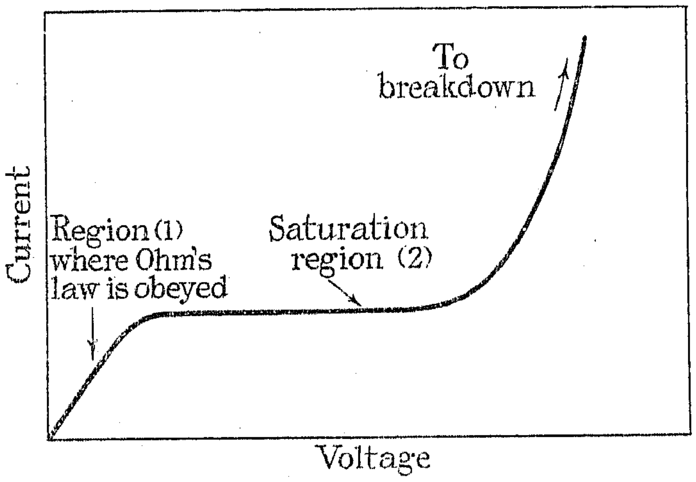

FIG. 1.

This conception of the ionization mechanism is clarified by the polarity effects which Nikuradse found to exist with unequal electrodes. If the number of positive and negative ions produced per unit time and per unit area of electrode surface be the same, no difference in saturation current should occur whichever plate is made positive by the externally applied voltage. If, however, the number of negative ions per unit time and area preponderates, the saturation current should be greater when the larger electrode is connected as cathode, and vice versa. Thus if carriers of only one sign arise, then $I_s^-/I_s^+ = F/f$ for negative ionization, and $I_s^+/I_s^- = F/f$ for positive ionization; where F and f are the large and small electrode areas, I_s^- is the saturation current when the large electrode is cathode, and I_s^+ is the saturation current when the large electrode is anode.

His experiments on purified chlorbenzene with perfectly clean copper electrodes for which $F/f = 1 \cdot 81$, showed that I_s^-/I_s^+ was equal to $1 \cdot 70$, from which a predominance of negative carriers may be concluded. It was found that this polarity effect was more pronounced the purer the liquid and the cleaner the electrode surfaces, and became smaller with time of contact. After a long period of contact under the influence of current passage the effect actually reversed, by which time the electrodes were seen to have acquired a characteristic sheen. This indicates an electrochemical action at the electrode surface, which is probably of importance as a secondary effect in the mechanism of ionic production.

In liquids which have not been subjected to prolonged processes of chemical purification, the ionization which may be regarded as characteristic of or inherent in the liquid in a purified state and with clean electrodes, under given external conditions, tends to be submerged by the ionization which results from the presence in the liquid of impurity in dissociated form. Small quantities of electrolytic impurity, which can be removed only with great difficulty by distillation, may produce a number of ions which is relatively large compared with that normally present.

There is considerable evidence to show that the lower the dielectric constant characterizing a liquid the lower its conductivity. The establishment of a relation between the chemical constitution and the conductivity, to permit prediction of the dielectric properties of a liquid from its chemical structure, is rendered difficult, however, by the need for complete removal of such impurity. The need applies equally to undissolved particles of impurity. The only measurements dealing directly with the importance of the latter appear to be those made by Stock,* who studied the effect of a fine suspension of carefully-dried quartz sand in certain hydrocarbon liquids. The conductivity was found to increase on addition of the sand. It is not certain, however, that the sand, though dry, was free from soluble surface impurity.

(*b*) *Insulating Oils.*

Of more significance to the electrical engineer than chemically definite compounds are the complex and somewhat undefined mixtures of hydrocarbon liquids which constitute the insulating oils. These vary widely in viscosity and contain paraffinic, naphthenic, and aromatic hydrocarbons, in varying proportions depending on their source. Paraffinic hydrocarbons have smaller dielectric constants than the naphthenic, and these in turn lower than the aromatic oils. In a highly refined state such oils exhibit a current saturation region under increasing d.c. potential, and residual conductivities of the same low order of magnitude (10^{-18} mho) as the purest simple liquids.*

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* See Bibliography, (3).

† *Ibid.*, (4).

* See Bibliography, (5).

At the present time scarcely anything is known of the mass, mobility, and character, of the charge carriers in insulating oils, and as to whether the carriers involved in the final steady-state conductivity are the same as or different from those which give rise to the larger initial conductivity.

The important liquid impurities in these oils are usually moisture and the products of oxidization processes.† The chemical changes which occur in mineral oils during their contact with, and due to the absorption of oxygen from, the air, are complex and depend on the constitution of the oil. The usefulness of a particular oil for insulation purposes depends primarily on its stability against such changes. This stability does not necessarily increase continuously with the duration of the refining process, and over-refinement may be as detrimental to the subsequent electrical properties as under-refinement.‡ It depends on the absence of oxygen and of double bonds in the original molecule. The velocity of the chemical changes increases with rise in temperature, and the oxidization process may be accelerated by other causes, which Gemant§ summarizes as follows: (1) admixtures of foreign substances, particularly metals with multiple valency, which act as catalysts; (2) boundary surfaces of suspended solid particles which act as gas-adsorption agents and accelerate oxidization partly by causing a greater concentration of reactive groups and partly by activating the gas molecules; and (3) electrolytic processes which cause unstable radicals to become positively charged at the anode and thus facilitate their combination with oxygen or hydroxyl ions.

The final product of oxidization is always an acid, which may become dissociated into ions, particularly in the presence of moisture. The intervening and undissociated final products are probably all of polar molecular structure and, while not contributing in this form to the direct-current conductivity, may be of distinct importance in governing the power loss in alternating electric fields. This aspect of the oxidization process is discussed later.

Of the moisture frequently associated in practice with insulating oils only a small proportion may be dissolved, and much of it may exist in the form of a suspension. The size of the suspended particles will depend mainly on the quantity of moisture present. Such oils usually contain also undissolved solid matter in the form of a colloidal suspension. This applies particularly to oils of large molecular size, and therefore of high viscosity, in which some specially long molecular chains, being solid even at room temperature, become precipitated as a dispersed phase in the rest of the oil.

From the electrical behaviour of insulating oils it seems probable that carriers of widely different mobilities, some of greater than individual molecular dimensions, are involved in the conduction process. Several suggestions as to their character have been put forward, based on the assumption that a number of ions are always present in the free state in these liquids.

The probability that these ions, by virtue of their intense electric field, surround themselves with an atmosphere of neutral molecules to form large aggregates, has been inferred by several authors.* These condensed molecules move with the ionic nucleus under the applied electric stress, and hence determine its mobility and, along with other factors, the resulting conductivity.

Particles of suspended colloidal material carry, as a rule, an electric charge of a sign depending on the nature of the substance. According to Böning† and others, these particles adsorb on their surfaces liquid ions of the opposite sign to produce an aggregate consisting of a double layer of opposite charges, of which, however, the outer layer is less closely bound than the inner. (It is more likely that a series of such layers of charges exists, corresponding to a gradual fall of potential from the inner surface layer outwards, although this does not seriously modify the original conception.) When a continuous electric stress of sufficient magnitude is applied, the outer layer of charge is detached and passes to one electrode, while the charged colloidal particle left moves towards the other electrode.

A further possibility has been based on Walden's‡ suggestion of a type of natural dissociation arising in the complexity of the organic molecular structure. His work points to a lack of homogeneity even in the purest liquids, and to the presence of molecular groups, probably unstable, other than the simple groupings by which the liquid is usually recognized. Whitehead§ has applied this conception to the insulating oils, in which he pictures the probable presence of a variety of molecular complexes and groupings resulting in a heavy, slowly-moving type of ion, which is subject to wide variation in properties with the value of the electrical intensity, and with other external influences. He regards this molecular complexity as a determining factor in the initial conductivity, and interprets the observation that the initial current in highly refined oils increased more than in proportion to the voltage as indicating a secondary ionization effect by which a greater and greater proportion of the complex molecular groups are split up into ions. According to Whitehead, reduction in the initial conductivity is to be looked for first by careful purification, but generally by the experimental selection of oils having the most stable molecular structure.

In addition to the oxidizing effect of absorbed oxygen, dissolved gases other than oxygen are detrimental when the applied voltage becomes sufficiently high to cause ionization of the gas. This ionization produces an increase in the number of conducting particles and a rapid increase in the d.c. conductivity with voltage, as is evidenced in the ascending region of Fig. 1, while accompanying chemical changes in the oil also result from bombardment of the oil molecules by the generated electrons and ions.‖ The effect of ionization of absorbed gas on the power loss in mineral oils has sometimes been found to be appreciable.[*] The magnitude of the observed loss increased with increase in the applied voltage. It is clear that investigations at high stresses cannot give reliable information of the true electrical characteristics of dielectric liquids unless the influence of dissolved gases is removed completely.

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* See Bibliography, (6).

† *Ibid.*, (7)

‡ *Ibid.*, (8).

§ *Ibid.*, (9).

* See Bibliography, (10), (11), and (12).

† *Ibid.*, (13).

‡ *Ibid.*, (14).

§ *Ibid.*, (15).

‖ *Ibid.*, (9), p. 114.

(C) ANOMALOUS CONDUCTIVITY.

When a direct voltage is applied to a liquid dielectric, the conduction current decreases with time, in some cases extremely slowly, from a high initial value to a final steady value which may be many times less than the initial current. The complete explanation of the phenomena responsible for this decay in conductivity is still lacking. It probably embraces several factors, the possible character of which will be reviewed.

(a) "*Electrical Cleaning.*"

Many attempts have been made to explain the decay on the basis of an "electrical cleaning" action. When dissociated impurity is present, many of the impurity ions will have been discharged electrolytically at the electrodes before the current becomes stationary, with the consequent removal from the liquid of part of the extraneous cause of ionization. The operation of this effect must show itself in a reduced value of the subsequent initial conductivity. The time taken for the final steady conducting state to be attained, and the ratio of the initial to the final conductivity, are indeed markedly dependent on the degree of purification, the former decreasing and the latter frequently tending to increase,[†] owing to decreasing final conductivity, with increasing dielectric purity.

In contrast, however, to Nikuradse's observation[‡] that the time dependence of the current disappears in mineral oils without excessive purification, Whitehead observed, with reference to insulating oils, that even after the most careful conditions of preparation an initial conductivity much greater than the final value remained. Since, moreover, the phenomena of current decay is frequently associated with liquids which exhibit complete recovery of the original initial conductivity when the voltage has been withdrawn for some time,[§] the operation of an electrical cleaning action leading to the complete removal of ionic sources cannot be regarded as more than a partial explanation in the general case.

Where the products of electrolysis are appreciable, or where suspended matter is carried to the electrodes by the current passage, it is possible that they may react indirectly on the conductivity value to a continuously increasing extent with time by the formation of an adsorbed layer of high-resistance material on the electrode surfaces.

(b) *Comparison with Ionized Gases.*

It has been mentioned already that many workers have assumed the process of conduction in liquid dielectrics to be of the same type as that in ionized gases. According to the theory of gaseous conduction, deficits in the number of ions of both kinds arise in the immediate vicinity of the electrodes, with a consequent decrease in the specific conductivity in these regions as compared with that in the intervening space, where the distribution of ions is the same as that existing before the application of the potential difference. Simultaneously with the gradual formation of these high-resistance regions a decrease in the overall conductivity occurs. The gas theory is considered by Black and Nisbet[*] to be a special case of a general theory advanced in a previous paper on oils by Black,[†] which attributed the fall of current with time to the formation of high-resistance sheets, of unstipulated nature, at one or both electrodes. With this mechanism the recovery of the original conductivity on voltage-removal results from the gradual disappearance of the contact resistances, and no discharge current is to be expected. Further, since the current flowing during charge is the same throughout the space between the electrodes, a non-uniform potential distribution, with sudden drops at the electrodes, is a necessary consequence of the presence of these high-resistance regions.

It is unlikely, however, that the deficit in the number of ions in the vicinity of an electrode will be the same for both kinds of ions. The motion of ions of opposite sign in reverse directions under the applied potential difference tends to withdraw the ions of one sign from the neighbourhood of the electrode of the same sign, i.e. to produce an excess of negative over positive ions near the positive, and of positive over negative ions near the negative, electrode. This constitutes the formation of space charges, in addition to the above-mentioned decreased specific conductivity, in these regions. The magnitude and distribution of these space charges depends on the velocity with which the original ions are withdrawn, the rate of regeneration of new ions, the rate of diffusion and recombination, and probably other factors. The central region between the electrodes, in which the original density of both positive and negative ions is retained, may be expected to become thinner with increased time of voltage application. The natural consequence of such inequalities in charge distribution is the production of a polarization potential which, in opposing the applied e.m.f., causes the current to decrease with time.

The conditions governing space-charge formation in a medium containing ions of constant and equal mobility have been discussed by Herzfeld.[‡] He has shown that the building-up of large space-charge fields is due to the fact that the current flow disturbs appreciably the equilibrium between dissociation and recombination of ions, and concludes that such space charges can arise only if the current has values which lie in a restricted range near the saturation current. If the current is very small compared with the saturation value, the ionization-recombination equilibrium is sustained in the main, except in the immediate neighbourhood of the electrodes, so that the space-charge formation is small. On the other hand, if the current is very close to saturation, a uniform field distribution results since the ions are then removed so quickly that no space charge can accumulate. This is probably only a partial statement of the case as it concerns an insulating oil, in which ions of widely differing mobilities are likely to be present.

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[*] See Bibliography, (16) and (17). [†] *Ibid.*, (15).
[‡] *Ibid.*, (18). [§] *Ibid.*, (11), (19), and (20).

[*] See Bibliography, (21). [†] *Ibid.*, (19). [‡] *Ibid*, (22).

The phenomena may be expected to appear the more readily the smaller the number of ions present, i.e. the lower the conductivity.

The fact that highly refined insulating oils have been found to show a saturation characteristic in the residual conductivity is in keeping with a comparison of their behaviour with that of ionized gases.

(c) *Evidences of Non-Uniform Potential Distribution and Space Charges.*

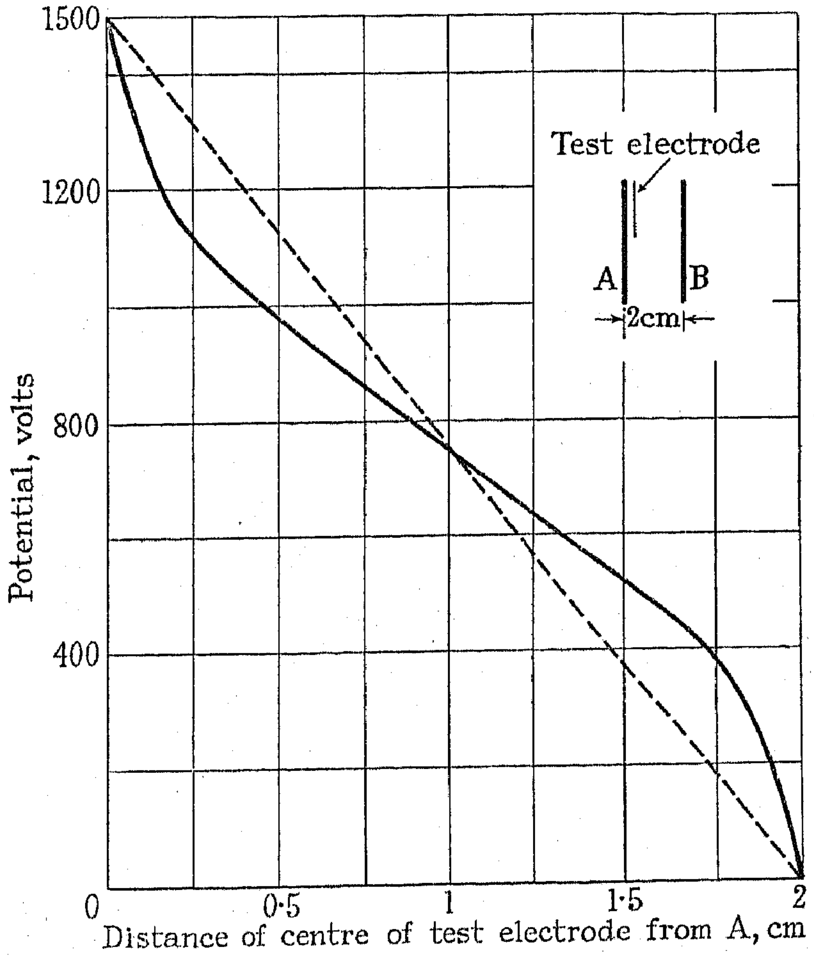

FIG. 2.—Whitehead and Marvin: potential distribution in transformer oil.

A and B are parallel plate electrodes immersed in oil.
The measurements were made after the current had been flowing for 30 minutes.

The experimental work of recent years has produced many evidences of non-uniform potential distribution under steady applied voltage. In some cases the field distortion has been found to be symmetrical about an axis midway between the electrodes, suggesting equal mobility of the positive and negative ions. Whitehead and Marvin,[*] for example, in a series of measurements on a transformer oil (referred to later as oil B) taken 30 minutes after the application of voltage, observed that the potential gradient in this central region was 40 per cent less, but at the electrodes many times greater, than the geometric value. It is seen from Fig. 2 that the non-uniformity extends a considerable distance into the body of the oil. The potential distribution remained uniform throughout the oil for from 15 to 30 seconds on the first application of voltage, after which interval it changed rapidly and reached a final steady value 5 to 10 minutes later. A simultaneous record of the charging current (Fig. 3) shows that the period during which the potential gradient at a given point is changing most rapidly is also that in which the rate of current-decrease is greatest. This would be expected if the fall in current were due to the development of a back-e.m.f. due to space-charge formation, of which direct experimental proof was obtained by Whitehead and Marvin. From the potential-distribution curve of Fig. 2, Herzfeld[*] has calculated the mobility of the ions concerned as $3 \cdot 5 \times 10^{-6}$ cm per sec. per volt per cm, and estimated them to contain approximately 110 atoms. This corresponds roughly to 2 molecules, since the boiling point of the oil (290° C.) suggests that the oil molecule is composed of about 45 atoms.

Since the current continued to decrease, long after the attainment of a steady field distribution (Fig. 3), it is obvious that some mechanism continued to operate without disturbing this distribution. This may have corresponded to a condition in which ions were being removed uniformly at a greater rate than that at which the processes of natural production could replace them.

Similar field distortion, but of much smaller magnitude, has been recorded by Schäfer[†] for a transformer oil of specific conductivity 10^{-12} mho. For the same oil in a more conducting state, the specific conductivity being 10^{-11} mho, however, the potential distribution between the electrodes was linear.

Other workers, in measurements on simple liquids, have found the field distortion to be unsymmetrical about the central axis, with the distortion at the cathode far more marked than that at the anode.[‡] In contrast to the observations of Whitehead and Marvin mentioned above, Dantscher[§] records that a strong field distortion was built up in a somewhat impure chlorbenzene immediately after voltage application. This field distortion was found to disintegrate with time as the charging current decreased towards its final steady value.

Direct experimental proof of the existence of space charges in insulating oils under steady electric stress has also been given in the work of Black and Nisbet,[||] and, more recently, of Gemant.[¶] The method adopted by the latter consisted in locating a porous paper shell close to an electrode and measuring the charge on the contained oil on its removal from the condenser immediately after the switching-off of the applied voltage. In this way he showed that the rise in the space charge was approximately proportional to the applied potential, that there was no polarity effect, and that only oils which were essentially free from moisture gave evidence of space-charge formation.

The building-up of space charges under stress leads at once to the expectation of discharge currents during the recovery of the dielectric medium on its subsequent short-circuit. Black and Nisbet were unable to observe the presence of such currents, however, in the oils studied by them in the above connection. Whitehead and Marvin found no evidence of an initial high value of current corresponding to a normal residual charge, and indeed the only suggestion of residual charge was limited to a current which decayed relatively slowly and was of such low value as to be difficult to detect. The observations of these workers on the absence of discharge currents are therefore of interest. The latter remark that "on short-circuit, as the space charges recombine in the liquid, a part also passes into the electrodes in the absence of an external e.m.f. and recombines through the external circuit, this forming a current in the opposite direction."[*] Black and Nisbet deal with the matter as follows: "If we assume that conduction in liquid dielectrics is similar to that in gases, then the mobility of the ions is the same everywhere within the liquid, as is also the dielectric constant. It is, then, not unreasonable to expect that on short-circuit the portion of an accumulated space charge which will be attracted to an electrode would be just sufficient to neutralize the induced charge on it, and such being the case, no residual discharge currents would flow in the external circuit. If there are two space charges of opposite sign, they will partially neutralize each other on short-circuit, but the above argument is practically unaffected."

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[*] See Bibliography, (11).

[*] See Bibliography, (31). [†] *Ibid.*, (23). [‡] *Ibid.*, (24), (25), and (26). [§] *Ibid.*, (27) and (28). [||] *Ibid.*, (21). [¶] *Ibid.*, (29).

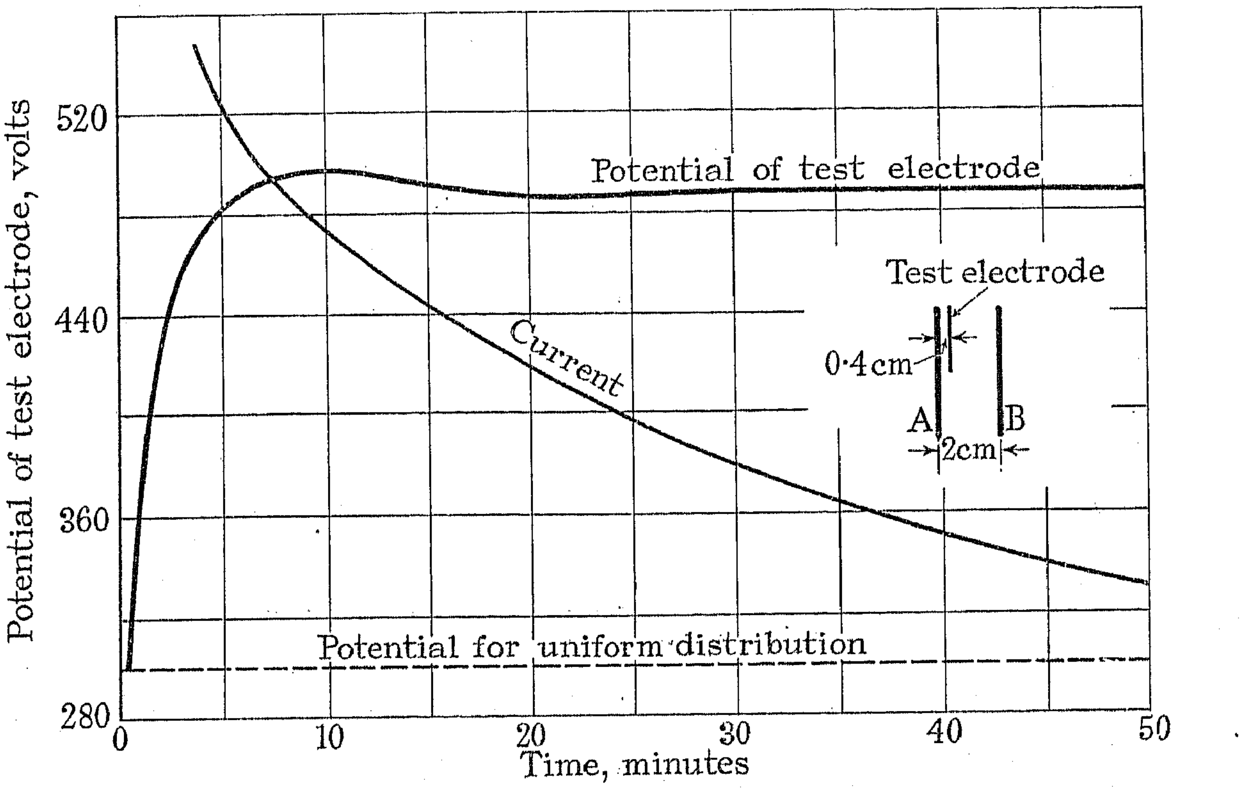

FIG. 3.—Whitehead and Marvin: transformer oil.

A and B are parallel plate electrodes immersed in oil.

The latter authors showed also that high-resistance regions present at the electrodes disappeared on short-circuit more slowly than the space charges, and that they can exist after the disappearance of these charges. Whether this is to be expected in a particular case depends on the rate of disintegration of the space charges under the electrical forces involved, as compared with the rate of production of new ions to replace the deficit in the total number of ions from which these high-resistance regions result.

(*d*) *Effects on Voltage Reversal, and Evidence of Another Type of Space Charge.*

Valuable information has resulted from studies of the current/time curve on reversal of the steady applied voltage after the attainment of the residual conducting state in the original direction. Whitehead and Marvin[*] have made measurements of this type on two samples of a transformer oil. Oil A was of the highest grade of insulating oil, and had a residual conductivity of the order of 2×10^{-16} mho per cm cube. Oil B was a slightly deteriorated sample of the same oil, in the sense that it had been in contact with air for some time and under approximately similar conditions of stress showed a conductivity from 7 to 8 times that of oil A. The potential-distribution curves of Figs. 2 and 3 refer to this oil. The behaviour of the two oils on first application of potential differed essentially. The initial value of the conduction current for oil B was closely proportional to the applied voltage, while that of oil A increased more rapidly than the voltage. Also, while the charging current in oil A decreased rapidly from the start and reached its final value after about 3 seconds, that in oil B remained approximately constant over an interval of a second or more and its subsequent decay lasted for several minutes.

On rapid reversal of the voltage applied to oil A, the conductivity remained sensibly unchanged at its residual value. This applied also for oil B, but only over a period of about 1 second; after this interval the current rose rapidly to a maximum which was sometimes as large as 40 times the constant current before reversal and from 2 to 3 times the initial value of the charging current when voltage was applied to the neutral oil, the ratio increasing with increasing field strength. The maximum occurred at from 2·5 to 7 seconds after reversal. This peak was not evident for low values of the field strength, but for high values was sometimes followed by a second peak of much lower value before the current fell to a final steady value again. In measurements on transformer oils, Black[†] found similarly that the reverse current passed in some cases through a single maximum, and in others through two displaced maxima. The magnitude of the reversed current was dependent on the previous polarity of the two electrodes. These effects are shown in Fig. 4, from which it is seen that the current variations occur much more sluggishly than in Whitehead's measurements. In later work on paraffin oil, Black and Nisbet[*] showed that the current maximum could be more than twice the initial charging current value. These high peak values of the reverse current cannot be accounted for solely by a polarization potential, owing to space-charge formation of the type discussed previously, assisting the reversed applied e.m.f.

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[*] That is, the opposite direction to that of the expected discharge.

[*] See Bibliography, (11).

[†] *Ibid.*, (19).

Should the ions experience, for some reason, an opposition to their discharge at the electrodes, the possibility arises of the formation of another type of space charge, owing to the accumulation of ions of a sign opposite to that of the adjacent electrode, in the vicinity of the electrodes. As such space charges accumulated under continuous stress, the resulting counter-e.m.f. would increase accordingly and cause the current to decrease with time of voltage application as before, until an equilibrium condition corresponding to the final conductivity was attained.

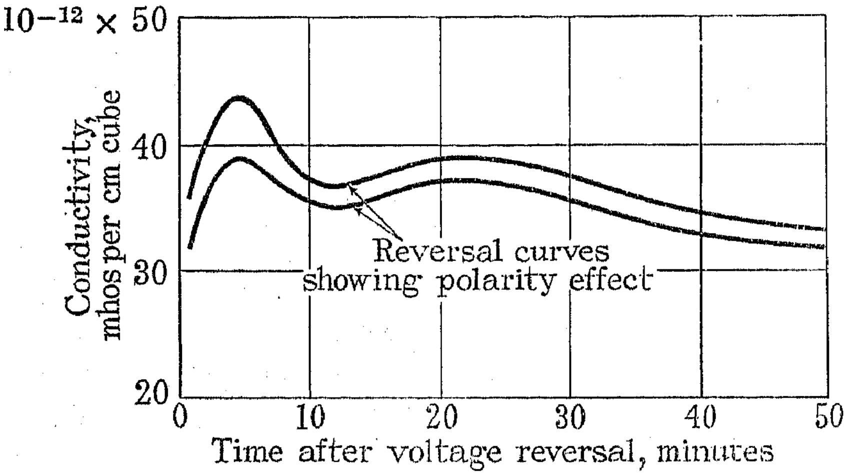

FIG. 4.—Black: transformer oil.

A mathematical treatment of the phenomena associated with the movement under applied voltage of a mobile layer of charge, such as might result from this kind of ionic accumulation at an electrode, through a dielectric medium of low ohmic conductivity, has been presented recently by Schumann.[†] When a field strength, such as that of a reversed potential, sufficient to set the layer in motion towards the opposite electrode is applied, it is shown that the current commences at a value in excess of the steady conduction current and ultimately decreases to this value. Between these two limits a maximum can appear in the current curve provided that the conductivity does not exceed a certain value which decreases as the electrode spacing increases. The ratio κ/σ of the dielectric constant to the specific conductivity is important in governing the duration of the process. If the ratio is small, the current change occurs rapidly, whereas if it is large, the current variations, including the appearance of a maximum, proceed slowly. The form of the current curve is also shown to be dependent on the magnitude of the applied voltage. Voltage effects on reversal have, in fact, been observed by Whitehead and Marvin, and by Black and Nisbet. The former workers found, as already mentioned, that the ratio of the current maximum to the initial constant current value on voltage reversal increased with increasing field strength, while the latter observed that the time t taken by the current to reach its maximum value varied, over a somewhat limited range of voltage V, according to the relationship $t = a/V^n$, where a and n are constants. Both of these effects appear consistent, in a general way, with Schumann's work. Further, if ionic accumulations occur at both electrodes, and if their mobilities, or rates of removal, under the reversed potential are different, then the appearance of two displaced maxima in the reverse-current curve seems not unlikely.

Both Whitehead and Marvin, and Black and Nisbet, sometimes observed irregularities in the charging-current curve on the re-application of voltage to a previously stressed oil. It is possible that these resulted from the presence of a space charge of the above type, formed during a previous charge, which had not disintegrated completely during the intervening recovery period.

Reverting again to the measurements by Whitehead and Marvin on oil B, it is of interest to compare the time taken for the potential distribution on the initial application of stress to attain a steady condition (5–10 minutes, see Fig. 2) with that which elapsed before the conduction current on voltage reversal passed through its maxima (2·5–7 seconds). This suggests the presence of two different types of ions which, according to Herzfeld,[*] may be distinguished as follows: (1) Large, slowly-moving ions which are discharged without appreciable accumulation at the electrodes, and which determine the non-uniform potential distribution of Fig. 2 and are involved in the subsequent slow decay in conductivity; (2) Smaller, more mobile ions, in much less quantity, which tend to accumulate at the electrodes without materially affecting the potential distribution and which are concerned in the short-time effects. The inability of the latter ions to discharge freely at the electrode surface may possibly be accounted for in terms of electrode surface reactions of a similar nature to those operative in electrolytic cells. In such cells it is known that an accumulation of electromotively active material occurs at the electrode surface, although opinions differ as to the form of this material and also as to the mechanism involved.[†]

This accumulated material exerts an active back-e.m.f., and it is probable that a back-e.m.f. produced in this manner is the source of the small and slowly varying reverse currents observable in simple dielectric liquids, such as nitrobenzene, in which traces of moisture remain and which give evidence of an electrical cleaning action under steady potential, on their short-circuit following a period of charge.[‡]

No generalized statement can be made of the relative importance of the several mechanisms outlined in determining the behaviour of liquid dielectrics under continuous voltage. This is likely to vary appreciably with the liquid studied. It is clear that before a complete understanding can be reached more information is necessary concerning the source, character, and physical properties, of the charge carriers in such media.

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[*] See Bibliography, (21). [†] *Ibid.*, (30).

[*] See Bibliography, (31). [†] *Ibid.*, (32). [‡] *Ibid.*, (33).

(D) Dielectric Absorption.

(a) Experimental Evidence.

As the result of a large amount of experimental evidence, the absence of absorption and corresponding discharge currents had come to be regarded as characteristic of liquid dielectrics. While this absence may have been real in some cases, it would seem a wiser decision, in general, to conclude from this evidence that the magnitude and/or duration of these currents had been too small to permit of their observation.

From short-time studies on a highly refined insulating oil (different from those discussed in the preceding section), commencing at about 0·002 second after the instant of voltage application, J. B. Whitehead[*] has been able to show the existence of a definite, though brief, dielectric absorption. Fig. 5 reproduces a typical charging-current record, in which three well-defined stages can be recognized. (1) An initial brief, rapidly descending, current of duration of the order of 0·04 sec. (This was found to represent a region of dielectric absorption by the presence of a corresponding discharge current $-i_1(t)$.) (2) An approximately constant value of conductivity within the interval 0·004 to 1 sec. (3) A very slowly-decaying conductivity reaching a constant value only after 30 minutes or more. The normal charging current is not included here.

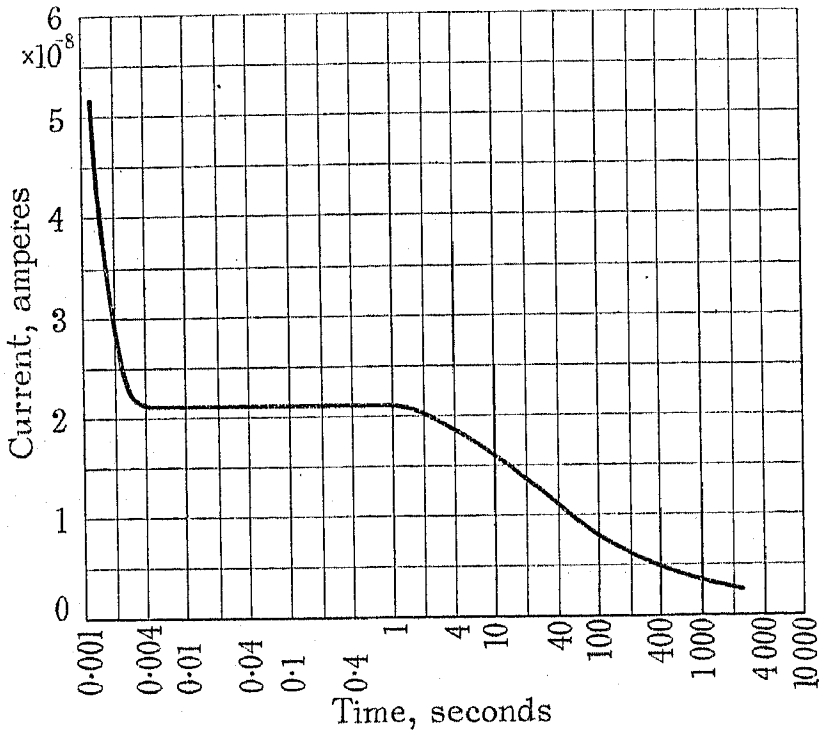

Fig. 5.—Whitehead: charging-current curve for transformer oil at 15 kV per cm and 30° C.

In a record taken at a temperature of 30° C. and with an applied field strength of 15 kV per cm, the behaviour during the first second of charge was found to be represented by the current relation

$$i_c(t) = (2\cdot 1 + 20\cdot 0\, e^{-1630t}) \times 10^{-8} \text{ ampere}$$

and on discharge by

$$i_d(t) = -\,20\cdot 0\, e^{-1630t} \times 10^{-8} \text{ ampere.}$$

The initial dielectric absorption decreased with increase in temperature, showing that it was a function, in some way, of the viscosity, and was difficult to measure at temperatures of 60° C. or more, and also in slightly deteriorated oil samples. In these cases the absorption, if present, became obscured by the greater value of the conductivity of phase (2).

Other similar measurements on a pure resin, which, while solid at ordinary temperatures, passed with increasing temperature through stages of slowly decreasing viscosity to a free-liquid condition at about 120° C., will be discussed in Part 2.

Although direct study of the mechanisms which can account for the presence of absorption in liquid dielectrics is not readily possible because of the difficulty which attaches in general to the observation of absorption currents in such media, the same mechanisms must be responsible for causing power loss in alternating fields, so that a review of their possible nature is desirable.

(b) Absorption Mechanisms.

Each of the theories of dielectric absorption which have been presented leads to an expression for the current in terms of a certain characteristic time-constant or relaxation time. Thus, following the application of direct voltage to the dielectric medium, the current flow decreases exponentially with time, and is perfectly reversible on voltage removal and short-circuit. Should several processes, each characterized by a different time-constant, operate simultaneously, then, whether they be of the same or different origin, each must add an exponential term to the absorption current.[*]

Several of the theories of dielectric absorption have regarded the absorption current as due to the restricted movement of ions, and differ only in the physical conception of the process.

If the dielectric medium is inhomogeneous in structure and the component materials have different values of the ratio κ/σ, ionic accumulations occur on the boundary surfaces when a d.c. potential is applied across the medium. This leads to the formation of polarization e.m.f.'s which oppose the applied voltage and cause the external current to decay with time in a simple or a complex exponential manner depending on the number of different constituents. In his original conception of this mechanism, Maxwell[†] represented the component materials in stratified form, but later Wagner[†] showed that the behaviour is essentially similar for a medium in which a number of component particles with different values of κ/σ are distributed arbitrarily. More recently, in development of a suggestion by Murphy and Lowry, Miles and Robertson[‡] have evolved a theory for the type of inhomogeneity represented by a distribution in a non-conducting medium of poorly-conducting colloidal particles which are surrounded by ionic atmospheres of much greater conductivity. The particles are assumed to be spherical, and the adsorbed ions are depicted as a concentric conducting shell of which the thickness is small compared with the radius of the particle. Under applied unidirectional stress the ions are displaced within the shell, and the relaxation time of the absorption process is obtained in the form $\tau = 3\kappa a/(8\pi c^2 \lambda d)$ sec., where κ is the dielectric constant of the particle material, a the particle radius in cm, c the ratio of electrostatic to electromagnetic units, λ the conductivity of the shell in electromagnetic units, and d its thickness in cm. A complex exponential form for the absorption current can be explained on this basis in terms of an assemblage of colloidal particles of non-uniform size.

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[*] See Bibliography, (15).

[*] It may be mentioned at this stage that experimentally-obtained absorption-current/time curves for compound dielectrics, as in cables, have been represented frequently as of the form $i_1(t) = It^{-n}$, although, in general, no single value of n has been capable of expressing the behaviour of a particular medium over a considerable period of time. Representation as the sum of a number of decaying exponentials is more rational, since the absorption current then tends to a finite value at zero time, whereas with the above expression it tends to infinity, and is more consistent with physical expectations.

[†] See Bibliography, (1).

[‡] *Ibid.*, (34).

The preceding are all based on surface charges arising from heterogeneity in the structure of the dielectric medium. These are to be distinguished from the ionic mechanism associated with the building-up of space charges under stress which Whitehead has applied to explain the brief dielectric absorption recorded in Fig. 4 for a light transformer oil, and also the intimate connection between absorption and conduction observed in other work on waxes.* As was discussed in the preceding section, the formation of space charges leads at once to the expectation of discharge currents on subsequent short-circuit, and the difficulty arose of accounting for the absence of such currents in the experimental work there described. It is not unlikely, therefore, that short-time space-charge formations may occur which are perfectly reversible with respect to the external circuit, and adequate to account for the brief absorption shown in Fig. 4, although in what way the ions taking part in these formations differ from those concerned in the non-reversible process of anomalous conduction is not yet clear.

Quite distinct from these ionic mechanisms of dielectric absorption is that associated with the presence of molecular dipoles in insulating liquids, and developed by Debye.† Not all molecular structures are in perfect electrical balance, but in some cases, owing to lack of coincidence between the centres of the positive and negative charges, the molecule can be regarded as a permanent electric dipole. When a liquid containing such polar molecules is subjected to steady electric stress, two displacement currents arise. Firstly, there is the normal charging current, of infinitesimally short duration, corresponding to a displacement of electrons within the molecules, and the production of an induced molecular polarity. Secondly, there is an absorption current due to a gradual orientation of the polar molecules from a random distribution into the direction of the applied field. In contrast to the formation of space charges, no disturbance in the uniformity of the potential distribution should be associated with the occurrence of molecular orientation. The speed at which this orientation proceeds, and the rate of decay of the absorption current, depend on the size of the polar molecules, the temperature, and the viscosity of the medium. For a dilute solution of polar molecules in a non-polar solvent, this is specified by the relaxation time

$$\tau = 4\pi\eta a^3/(kT). \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where a = radius of the equivalent molecular sphere in cm, T = absolute temperature, η = coefficient of viscosity, and k = Boltzmann's constant ($1 \cdot 37 \times 10^{-16}$ erg per deg. C.).

The derivation of this relation is based on three assumptions: (1) That the dilution is such that interaction between neighbouring polar molecules can be neglected; (2) That the laws of an ideal gas may be applied, and use made of Boltzmann's constant and Avogadro's number; (3) That the viscosity coefficients (as ordinarily measured) and Stokes's law for falling spheres in a viscous medium, relate to the forces between polar and non-polar molecules. Recent experimental work indicates, however, that assumption (3), together with the representation of polar molecules as equivalent molecular spheres, does not hold rigorously—at least, not invariably so—in practice. For example, Debye* has found that the relaxation time of the same polar substance (orthodichlorbenzene) in several different non-polar solvents, such as benzene, carbon disulphide, etc., is not proportional to the viscosity of the latter as is predicted by equation (1). Further, attempts to derive values for the dimensions of polar molecules from this formula have frequently given results much lower than were to be expected from other data. This suggests the possibility that the derived dimension is not always that of the whole molecule, but is that of a constituent polar group orienting within, and relative to, the central part of the molecule. This behaviour is quite to be expected in the case of such polar molecules as can occur in viscous insulating oils of which the normal molecules are long-chain hydrocarbons. These calculations have been based on values of τ provided by a.c. measurements, such as will be discussed in Part 2, and on a mechanical determination of the viscosity. Here two points of uncertainty arise. Firstly, it may well be questioned whether the inner friction opposing the orientation of individual molecules is always given by the viscosity of the medium in bulk. Secondly, if the above expression for the relaxation time is to be directly applicable to the correlation of the behaviour in a.c. and d.c. fields, it is necessary that this inner friction should be independent of frequency. For colloidal materials it appears, however, that the viscosity coefficient as measured for steady motions is not the same as for high-frequency motions, and indeed that it tends to decrease appreciably with increase in frequency.†

The saturated hydrocarbons are sensibly non-polar,‡ and since highly refined insulating oils contain little or no unsaturated material, they contain in all probability very few polar molecules. In use they gradually decompose, however, largely owing to oxidization, and form various products—acids, esters, and some solid material or sludge—all of which are polar. This is shown by the gradual increase of dielectric constant which results from continued contact with the atmosphere.§

Such orientation need not be limited necessarily to individual molecules. It seems likely that complex groups of polar molecules, as postulated by Clark,‖ and the ionic dipoles suggested by Murphy and Lowry,¶

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* See Bibliography, (35).

† Ibid., (36).

* See Bibliography, (37).

† Ibid., (38).

‡ Ibid., (39).

§ Ibid., (40).

‖ Ibid., (41).

¶ Ibid., (10).

may be of distinct importance in governing the behaviour of dielectric liquids. The association of ions and neutral molecules to form large aggregates has been mentioned previously. This may well be followed by an association of aggregates, of positive and negative nuclei, to form ionic dipoles. The nuclei would be prevented from recombining by the associated molecules, and the dipoles formed might be fairly stable, according to Murphy and Lowry, since their formation would probably involve a decrease of potential energy. Since the dimensions of these polar groups and ionic dipoles would exceed appreciably those of individual polar molecules, the relaxation time of their orientation in a given medium would be very much greater.

Such ionic dipoles would be expected to separate into their constituent ions to an increasing extent with increase in the applied field strength, and as a result produce or contribute to a gradually increasing initial conductivity with voltage. This effect occurred with the transformer oil to which the curve of Fig. 5 relates; it has also been observed by other workers.

Part 2.—POWER LOSS IN ALTERNATING FIELDS.

(A) PREDETERMINATION FROM DIRECT-CURRENT CHARACTERISTICS.

A close relationship is to be expected between the behaviour of a dielectric medium in direct and in alternating electric fields. When an alternating voltage is applied, the only effects of importance, however, are those operative in the initial stages of the process under d.c. potential, that is, during a time-interval of the same order of magnitude as the period of the alternating supply.

J. B. Whitehead and his associates have concentrated on a correlation of the steady alternating behaviour of dielectric materials with their short-time d.c. characteristics. It has been seen that the initial current flow in a dielectric medium under d.c. potential may consist, in addition to the normal charging current, of (1) a reversible or absorption component, having a corresponding discharge current, and (2) an irreversible component.

Consider the first component. Any absorption effect, being perfectly reversible, must be responsible for power loss and a variation of dielectric constant when an alternating voltage is applied. A knowledge of the time variation of this component, as specified by a single or several characteristic time-constants, is sufficient to permit these quantities to be calculated to a high degree of accuracy. This is made possible by application of the Hopkinson* "Principle of Superposition." The method is perfectly general, and may be employed for computation whatever the nature of the absorption mechanism.

If such a current component be represented by the relation

$$i_4(t) = \beta C_0 e^{-\alpha t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

in which C_0 is the geometric capacitance of the condenser with dielectric, and β and α are constants of the medium for fixed conditions of temperature and electric stress ($\alpha = 1/\tau$), where τ is the time-constant of the absorption process), then the condenser admittance at a frequency $\omega/(2\pi)$ is given by

$$Y = \omega\left[B + j(C_0 + A)\right]$$

where

$$A = C_0\alpha\beta/(\omega^2 + \alpha^2) \quad \text{and} \quad B = C_0\omega\beta/(\omega^2 + \alpha^2)$$

For an absorption current consisting of n components of different time-constants, then

$$A = C_0\sum_1^n \frac{\alpha_1\beta_1}{\omega^2 + \alpha_1^2} \quad \text{and} \quad B = C_0\sum_1^n \frac{\omega\beta_1}{\omega^2 + \alpha_1^2}$$

A denotes the change in capacitance from the geometric value, so that

$$\frac{\Delta C}{C_0} = \sum_1^n \frac{\alpha_1\beta_1}{\omega^2 + \alpha_1^2}$$

while the loss angle δ is determined by the relation

$$\left(1 + \frac{\Delta C}{C_0}\right)\tan\delta = \sum_1^n \frac{\omega\beta_1}{\omega^2 + \alpha_1^2} = \text{Power loss per cycle}$$

The power loss under an applied alternating voltage V is then equal to $V^2\omega C_0\left[1 + (\Delta C)/C_0\right]\tan\delta$.

To this loss must be added that resulting from irreversible conduction. In his measurements on transformer oils,* Whitehead found that the conduction current remained constant over a period of the order of 1 sec. This period, though short, is nevertheless of relatively long duration compared with the period of normal a.c. supplies. The loss due to irreversible conduction can be calculated at once from this initial constant conductivity. It has been suggested by other workers, who have not observed the presence of absorption phenomena, that the rate of change of conductance in the initial stages of the conduction process under continuous voltage is zero, or very small.† If this is so, the power loss should be given entirely as $V^2\sigma_i$, where σ_i is this initial conductivity, as measured under equivalent continuous stress.

Whitehead has compared the measured power loss in transformer oils with the values calculated from the corresponding d.c. characteristics, and has found that it can be accounted for completely on the basis of the initial absorption and conductivity. Where absorption was not apparent, the initial constant conductivity proved sufficient. A reduction in power loss must result, therefore, from a reduction in the magnitude of these initial effects.

(B) VARIATION WITH FREQUENCY AND TEMPERATURE.

If a dielectric medium is devoid of absorption and is characterized by a constant initial conductivity, the power loss should be independent of frequency. Any component of loss arising from absorption is, however, a function of frequency, and an analysis of this variation provides an approach to a study of the responsible factors. For a single component of absorption current,

$$\left[1 + (\Delta C/C_0)\right]\tan\delta = \omega\beta/(\omega^2 + \alpha^2)$$

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* See Bibliography, (1).

* See Bibliography, (15).

† *Ibid.*, (20), (42), and (43).

This power loss per cycle is zero at zero frequency, passes through a maximum value $\beta/(2\alpha)$ at a frequency given by

$$f_m = \omega_m/(2\pi) = \alpha/(2\pi) = 1/(2\pi \times \text{time-constant})$$

and becomes zero again at infinite frequency (Fig. 6). Simultaneously a change in effective capacitance occurs from a value of $C_0[1 + (\beta/\alpha)]$ at zero frequency to C_0 at infinite frequency. The smaller the time-constant of the absorption process, therefore, the higher the region of frequency in which the loss-maximum and corresponding dielectric-constant variations appear.

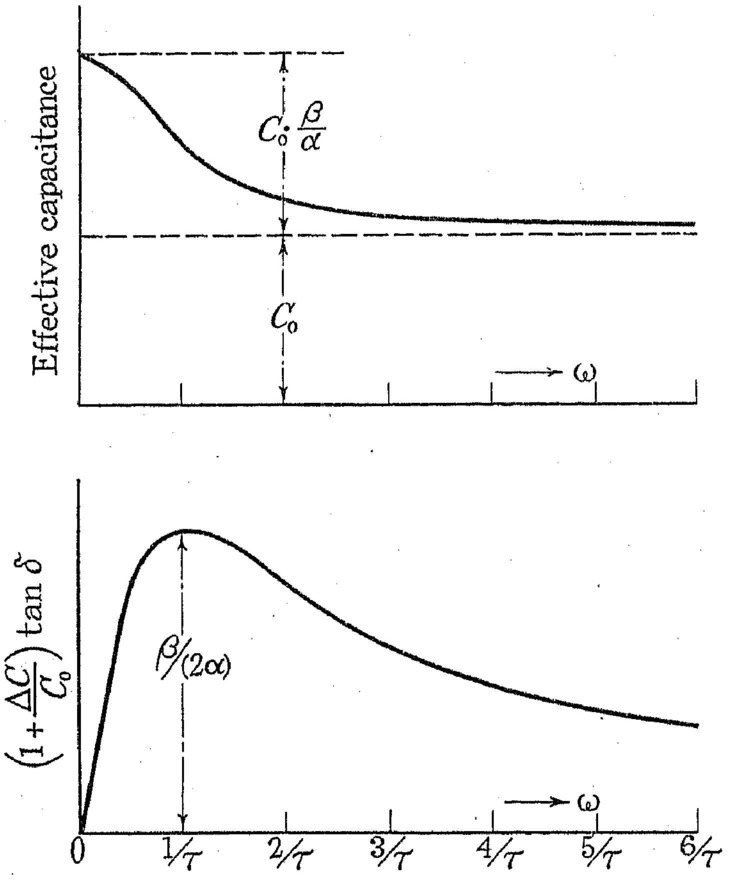

FIG. 6.—Variation of effective capacitance and power loss per cycle with frequency.

Similar conclusions follow directly from Debye's theory, as also from a discussion of this theory by S. Whitehead,* who develops a relation for the dipole power factor in terms of the physical coefficients of the material rather than in terms of the limiting values of the dielectric constant as employed by Debye. Following the latter, the behaviour of a medium consisting of a dilute solution of polar molecules in a non-polar solvent can be expressed in terms of a complex dielectric constant $\kappa = \kappa' - j\kappa''$, or a complex admittance $Y = \omega C_{vac.}(\kappa'' + j\kappa')$ where

$$\kappa'' = \frac{\omega\tau(\kappa_0 - \kappa_\infty)(\kappa_0 + 2)(\kappa_\infty + 2)}{(\kappa_\infty + 2)^2 + \omega^2\tau^2(\kappa_0 + 2)^2}$$

and

$$\kappa' = \frac{\kappa_0(\kappa_\infty + 2)^2 + \omega^2\tau^2\kappa_\infty(\kappa_0 + 2)^2}{(\kappa_\infty + 2)^2 + \omega^2\tau^2(\kappa_0 + 2)^2}$$

Here κ_0 and κ_∞ are the dielectric-constant values at zero and infinite frequency respectively. The latter is the smaller, to an extent depending on the number and moment of the polar molecules present, since these molecules are unable to orient themselves in sympathy with such high applied frequencies and their contribution to the dielectric polarization becomes negligible. τ is the relaxation time of the molecular orientation (see equation 1).

Proceeding as before, the power loss per cycle is obtained from the imaginary part of the dielectric constant in the form

$$\frac{\kappa'}{\kappa_\infty}\tan\delta = \frac{1}{\kappa_\infty}\cdot\frac{\omega\tau(\kappa_0 - \kappa_\infty)(\kappa_0 + 2)(\kappa_\infty + 2)}{(\kappa_\infty + 2)^2 + \omega^2\tau^2(\kappa_0 + 2)^2}$$

This is zero at both zero and infinite frequency, and passes through a maximum value $\frac{1}{2}(\kappa_0 - \kappa_\infty)/\kappa_\infty$ at a frequency given by

$$f_m = \frac{\omega_m}{2\pi} = \frac{1}{2\pi}\cdot\frac{1}{\tau}\cdot\frac{\kappa_\infty + 2}{\kappa_0 + 2}$$

Debye* has shown that the dielectric loss should be proportional to the square of the molecular electric moment. Thus for different polar molecules of about the same size in the same medium, having therefore about the same value of τ, an increase in the dipole moment should result in an increased energy absorption.

Increase of temperature tends to produce a decrease in the time-constant of the absorption process whatever its fundamental cause, so that the frequency at which the power-factor maximum occurs can be changed by temperature control. Thus if the absorption is due to an internal polarization arising from the formation of space charges, increase in temperature must increase the ionic mobility and decrease the time-constant of the ionic displacement. According to Debye's theory the relaxation time of the process of molecular orientation decreases both directly through T and indirectly through the viscosity η, as the temperature increases. If the absorption is due to inhomogeneity in structure, the effect of temperature change may be analysed in terms of the 2-layer composite dielectric of Fig. 7. The time-constant of the absorption current in this arrangement is given by

$$\tau = \frac{C_1 + C_2}{(1/R_1) + (1/R_2)}$$

The conductivity of the layers will increase with rise in temperature, owing on the one hand to greater dissociation and a consequent increase in the number of ions available, and on the other to a decrease in the frictional resistance to ionic movement, to produce a decrease in the time-constant. This applies equally to the Wagner conception, on which the conducting components are distributed throughout a dielectric medium. (It is readily shown that at the frequency at which the power-factor maximum occurs in the simple equivalent arrangement of Fig. 7, the resistance R of one layer is of the same order of magnitude as its capacitive reactance $1/(C\omega)$. This is of importance in connection with laminated materials in which one component layer is of high conductivity.)

The power loss per cycle and the dielectric constant vary in a similar manner with temperature at constant frequency as with frequency at constant temperature. Thus $[1 + (\Delta C/C_0)] \tan \delta$ passes through a maximum for variable temperature when the time-constant of the absorption mechanism becomes equal to $1/(2\pi f)$. Also as the time-constant becomes larger and larger, and α smaller and smaller accordingly, $\Delta C \rightarrow 0$, and $C \rightarrow C_0$; while for the reverse, as might occur with any mechanism at sufficiently high temperatures, $\Delta C \rightarrow C_0\beta/\alpha$ and $C \rightarrow C_0[1 + (\beta/\alpha)]$. Measurements with variable temperature are not so satisfactory, however, as those conducted at constant temperature and variable frequency, since the initial conductivity of liquid dielectrics, and the added component of loss to which it leads, vary appreciably over a temperature range. The component of loss due to conduction increases continuously with increase of temperature and accounts for the rising characteristic in the higher temperature-range of the curves of Fig. 12, to be discussed later. The association of this loss with an absorption component in the region of temperature for which this latter is continuously decreasing with further temperature-rise, produces a trough or V in the total-loss/temperature or power-factor/temperature curve about a point at which the two components become of the same magnitude.*

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* See Bibliography, (44).

* See Bibliography, (36) and (37).

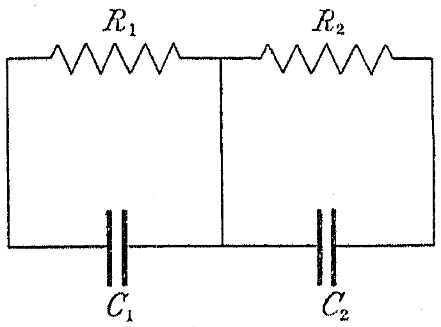

FIG. 7.—Equivalent circuit for a 2-layer composite dielectric.

The previously discussed mode of variation of the power loss per cycle and the dielectric constant with either frequency or temperature is independent of the source of absorption. The appearance of such variations in measurements on dielectric liquids of uncertain constitution is not sufficient, by itself, to permit of a decision as to the particular mechanism in operation, although a knowledge of the frequency at which the loss maximum occurs may be of great assistance in this connection. Granted the presence of polar molecules, their dimensions and the internal friction opposing their orientation determine completely, at a given temperature, the range of frequency in which their contribution to the power loss becomes of importance. This should apply equally if the polarized particles are ionic dipoles. The presence of polar molecules is usually to be expected in the dielectric materials of engineering practice, but, in view of the uncertainty of their composition, the physical data required for a theoretical determination of the critical frequency at which the dipole power-factor maximum should occur are in general unknown and are extremely difficult to obtain. For a dilute solution of nitrobenzene molecules, of which the equivalent radius is known to be of the order of 3×10^{-8} cm, in a solvent of viscosity similar to that of castor oil at room temperature, 10 poises, this critical frequency occurs in the region of 10^6 cycles per sec. Polar molecules or aggregates of much larger dimensions than those of the nitrobenzene molecule are probable in highly viscous mineral oils and resinous compounds, so that it seems possible for a dipole power-factor maximum to occur at quite low frequencies. Whether the necessary physical conditions can arise for its appearance at frequencies as low as 50 cycles per sec. is not yet certain, although, as discussed later, several workers have claimed satisfactory evidence on this point. Where optical measurements of the phenomenon of double electrical refraction, known as the "Kerr effect,"* are possible, they may be used to check the applicability of the Debye theory in a particular case. This effect is pronounced in media containing polar molecules, and its disappearance on sudden discharge of the dielectric medium should be governed by the same relaxation time as that of the dipole orientation. Similarly, the effect should fail to appear in an alternating field of frequency too high for the dipoles to follow.

The mechanism of ionic displacement differs from that of dipole orientation in that it signifies the formation of space charges under continuous potential, and a study of the short-time d.c. characteristics in this respect offers perhaps the most promising method of distinguishing between the two as explanations of dielectric loss in particular cases. Inhomogeneity in structure can be studied by microscopic analysis and can suggest the presence of conducting constituents as a cause of power loss. Although the Maxwell–Wagner theory is not quantitative, except in the form presented by Miles and Robertson, Gemant states that the associated power-factor maximum may be expected to occur at any part of the frequency range up to 10^5 cycles per sec.

(C) RECENT EXPERIMENTAL WORK.

In reviewing the work dealing with dielectric liquids of engineering importance which has appeared of recent years, it is proposed to consider first those contributions which lay emphasis on the importance of polar molecule orientation. Much of this work has been carried out on liquids of high viscosity at normal temperatures which are found to pass into an apparently solid state on temperature decrease without discontinuity in their electrical behaviour. The explanation of this would seem to be that the change of state does not indicate a discontinuous change in the actual environment opposing the motion of the polar molecules.

The serious discussion by engineers of this mechanism as a factor responsible for power loss in liquid dielectrics appears to have commenced with the work of Kitchin and Müller,† who studied the effect of diluting a commercial resin oil with a neutral transil oil of negligible power factor and low viscosity. The presence of polar molecules in the resin oil was demonstrated in optical studies of the Kerr effect. The variations of the power factor and dielectric constant of various mixtures at 10^6 cycles per sec. over the temperature range from 0 to 170° C. are shown in Fig. 8. The form of these curves is the same as those obtained on similar media by Dunsheath‡ in measurements at angular frequencies of 5 000 and 10 000, and by Emanueli[*] at several frequencies between 22 and 1 000 cycles per sec. The effects recorded in Fig. 8 agree qualitatively with the deductions which can be drawn from Debye's theory. The addition of transil oil reduces the power-factor maximum and the dielectric-constant change by decreasing the dipole concentration, and shifts the maximum to lower temperatures by reducing the viscosity. Fig. 9 shows the results at three different frequencies—60, 10^6, and 10^7 cycles per sec.—on a wood resin. It is seen that the power-factor maximum is sensibly independent of frequency and temperature, which suggests that the same mechanism is operative at all three frequencies. The small width at the peak of the 60-cycle curve as compared with the higher-frequency ones is accountable for by the fact that the rate of change of viscosity with temperature is much greater in the region of the former than of the latter. The power-factor curve for 60 cycles per sec. exhibits an upward trend above 100° C. It is suggested that the power factor due to dipole orientation has become so small as to be swamped by that arising from the rapidly increasing conductivity. Although the leakage becomes much greater at the higher temperatures attained in the radio-frequency measurements, its contribution to the total power factor remains submerged in that due to polar molecules.

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* See Bibliography, (45).

* See Bibliography, (9).

† Ibid, (46) and (47).

‡ Ibid., (45).

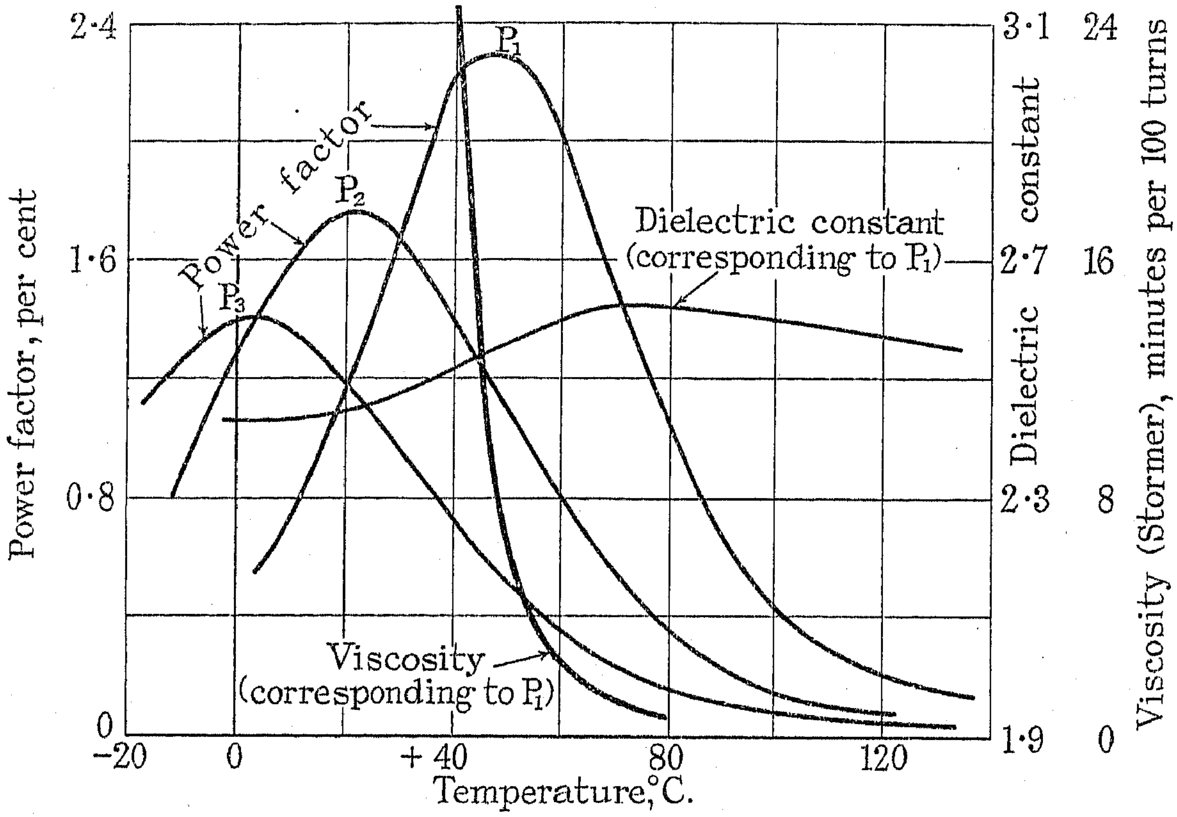

FIG. 8.—Kitchin and Müller: resin and transil-oil mixtures (frequency = 10^6).

(1) = 100 per cent resin oil (containing 50 per cent of resin).
(2) = 80 per cent resin oil, and 20 per cent transil oil.
(3) = 50 per cent resin oil, and 50 per cent transil oil.

Kirch and Riebel[†] have reported several studies of transformer oil-resin mixtures in various proportions at 50, 800, and 1 600 cycles per sec. in the temperature range up to 150° C. They found that the power-factor maxima for different mixtures were displaced to temperatures at which the viscosities were equal. This is to be expected from the relaxation-time relation (equation 1), if the difference in the absolute temperature at the several maxima is neglected. The results when analysed qualitatively give strong support to their proposal that the variations in power factor and dielectric constant with temperature and frequency are due to dipole orientation. In a more recent paper Kirch[*] supported these conclusions and presented evidence against the possibility that the loss maxima arose from the presence of conducting impurity. The loss in an impure resin was found to be dependent on the amount of oxiacid impurity only in the high-temperature range, where it was due entirely to conduction. Removal of the impurity hardly affected the magnitude of the loss maximum which appeared in the low-temperature region where the conductivity was small. On heating a pure resin for a prolonged period in air, the viscosity and oxiacid content increased, and were associated with an increase in this loss maximum and its transference to higher temperatures. Although the oxiacid content increased 100-fold, the loss maximum was only doubled. Fig. 10 relates to measurements at 50 cycles per sec. on two different resins and on a mixture of equal parts of the two. Each resin, taken independently (curves *a* and *c*), shows a loss maximum, and the mixture (curve *b*) shows a single maximum corresponding to an average viscosity. When the materials were stratified, however, both the independent maxima appeared. All of these are regarded as arising from dipole orientation. The curves of Fig. 11 are of great interest. They concern a stratified combination of an artificial insulating material—plexigum—and a resin. Independently, each gives a loss maximum, as seen in curves (*a*) and (*b*). In the combination (curve *c*) these reappear at the same temperatures, but, in addition, a third, a Maxwell–Wagner maximum, occurs at a temperature where one of the layers has become highly conducting. On increasing the frequency to 800 cycles per sec. each of the maxima was displaced to a higher temperature, the two former (Debye) ones to a region of lower viscosity, and the Wagner maximum to a temperature where the conductivity of the highly conducting layer had increased to an extent proportional to the frequency-change.

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[*] See Bibliography, (48).

[†] *Ibid.*, (49).

[*] See Bibliography, (50).

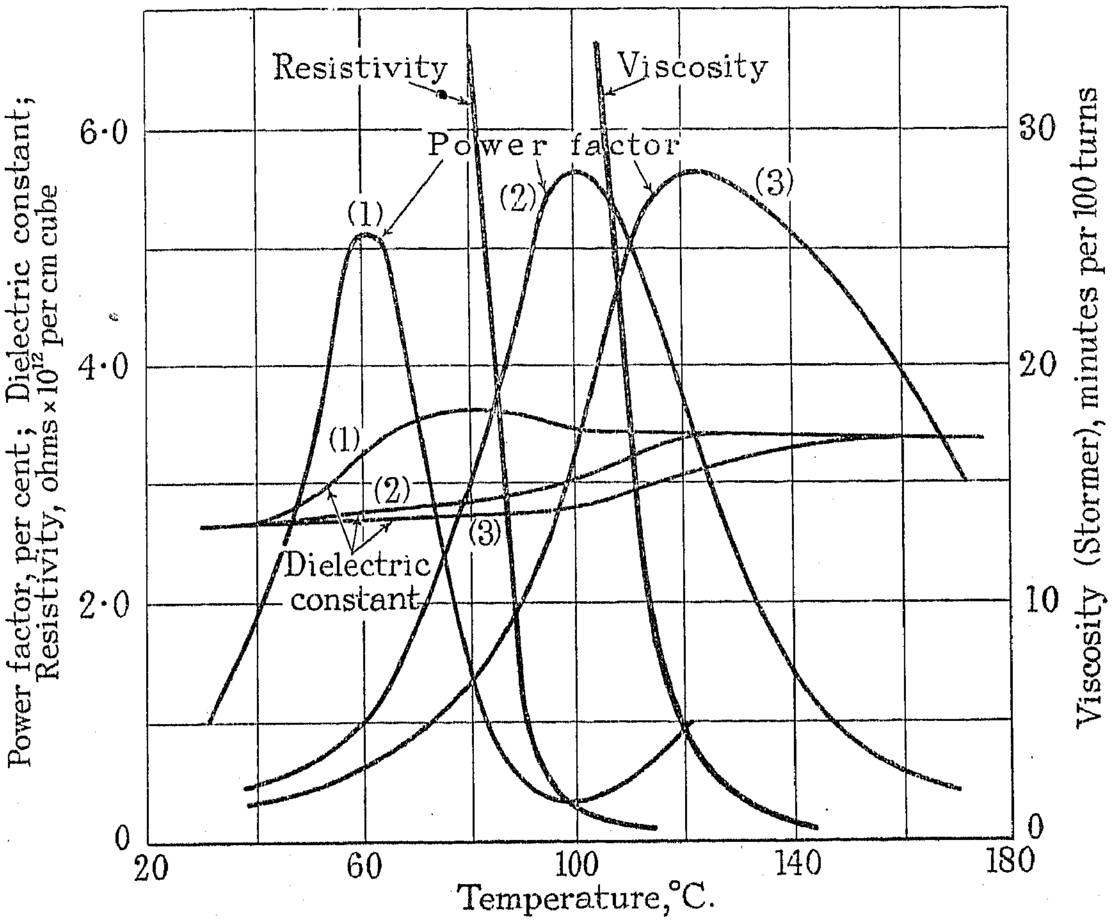

FIG. 9.—Kitchin and Müller: wood resin.

(1) Frequency = 60.
(2) Frequency = 10^6.
(3) Frequency = 10^7.

Ornstein and Willemse* claim to have presented additional evidence in favour of molecular orientation as the important cause of dielectric loss in measurements on samples of transformer oil at several frequencies between 50 and 3×10^6 cycles per sec. and at temperatures up to 150° C. A close correlation was observed between the changes in value of the Kerr constant and those of the dielectric constant and power loss. Race† has accounted for somewhat similar results on a viscous mineral oil on the same basis.

In spite of the sensibly unknown structure of the materials tested, attempts have been made by several authors to show quantitative agreement in their results with the Debye theory. Thus both Kitchen and Müller, and Race, obtained values for the size of the postulated polar particles which were regarded as of the correct order of magnitude, although the conclusion of the former authors was questioned later by Johnstone and Williams.‡ Also the measurements of White and Morgan§ on a series of glycols and on resin oils, over a wide temperature range and at several frequencies between 10^3 and 10^5 cycles per sec., are apparently in close quantitative agreement with this theory in certain cases.

These same authors have since extended their measurements to study the connection between the dielectric properties, as expressed by the real and imaginary parts of the complex dielectric constant, and the chemical constitution of a number of samples of chlorinated diphenyles.* These samples, described as differing in

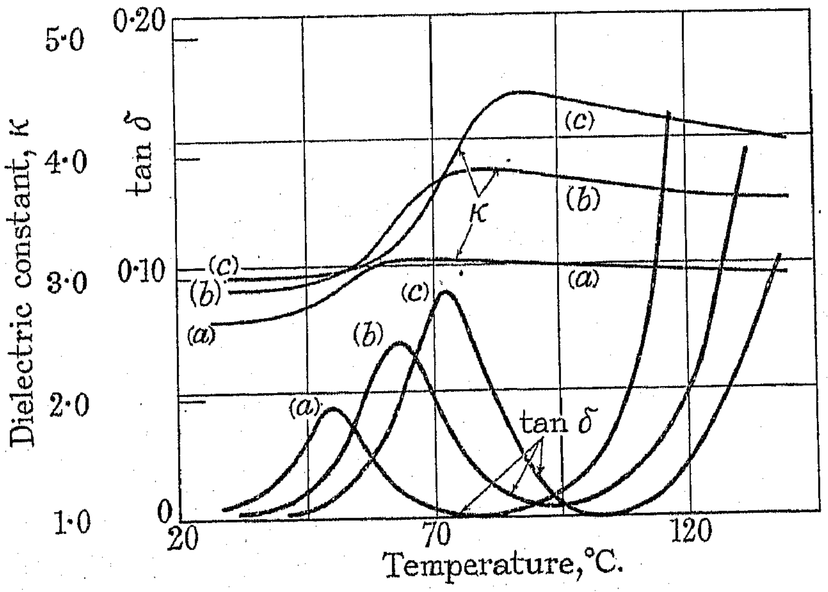

FIG. 10.—Kirch (frequency = 50).

(*a*) and (*c*): Two different resins.
(*b*): Equal mixture of the two resins.

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* See Bibliography, (51). † *Ibid.*, (52). ‡ *Ibid.*, (53). § *Ibid.*, (54) and (55).

* See Bibliography, (56).

chlorine content, ranged in physical properties at 25° C. from a mobile oil to a brittle resin. The materials showed quite analogous behaviour; each gave a loss maximum within the temperature range − 40° to + 80° C., the maximum appearing at a higher temperature the greater the viscosity, and this behaviour is again explained in terms of the polar molecules which the materials may be expected to contain.

The development of polar characteristics in insulating oils during their deterioration by oxidization on prolonged heating in air has been studied by Stoops* in a series of measurements of dielectric constant and power factor over a temperature range from − 80° to + 100° C. at frequencies of 5×10^5 and 10^6 cycles per sec. It is shown that the decomposition in transformer oils can be followed closely by measurement of the dielectric constant, and that such measurements offer a convenient method of differentiating between several oils as to their tendency to deteriorate. In similar work Race† found that oxidization increased the dielectric loss at high frequencies but did not change the frequency at which the loss maximum occurred. If the applicability of the Debye theory be accepted, this means that oxidization increases the number of polar molecules or particles per unit volume but does not change their size. The average radius calculated from the measurements was considerably smaller than that expected for an oxidized oil molecule, and this led to the conclusion that the whole molecule does not orient but rather that the polar group moves with reference to the rest of the molecule. The increases with oxidization of the high-frequency loss and the spreading on water, the latter of which depends on the polar content, were found to be proportional. A comparison of these variations with those of the conductivity showed that oxidization at high temperatures has a greater effect in producing polar molecules than particles capable of carrying charge.

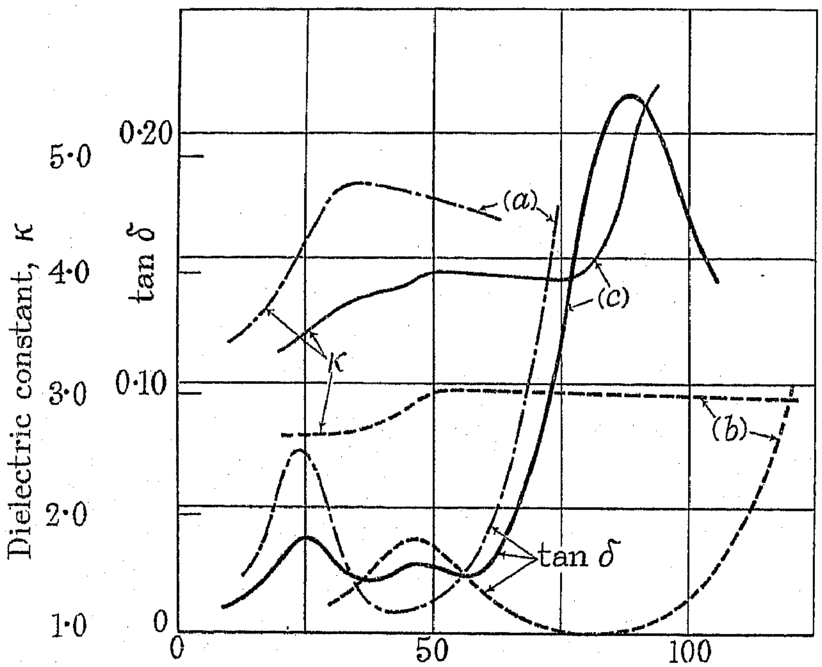

FIG. 11.—Kirch (frequency = 50).

(a) = Plexigum alone.
(b) = Resin alone.
(c) = Stratified combination of plexigum and resin.

The conclusion of Kitchen and Müller that dipole orientation was the important factor in their dielectric-loss measurements at power frequencies was subsequently criticized adversely by Hamburger,* who suggested that this type of loss was likely to be unimportant for frequencies lower than 10^4 cycles per sec. A similar restriction has been proposed by Gemant.† In a series of tests on transformer oils at constant room temperature over a frequency range from 50 to 10^6 cycles per sec., the latter found that the loss angle of two samples, after correction for the d.c. conductivity, decreased from a high value at low frequency but commenced to increase again as the frequency approached 10^6 cycles per sec. This suggests the growing importance of a second source of loss at the higher frequencies. Gemant concludes that the loss in oils over the above frequency range has to do with both the Maxwell–Wagner and Debye mechanisms, the latter becoming of importance only at the higher frequencies.

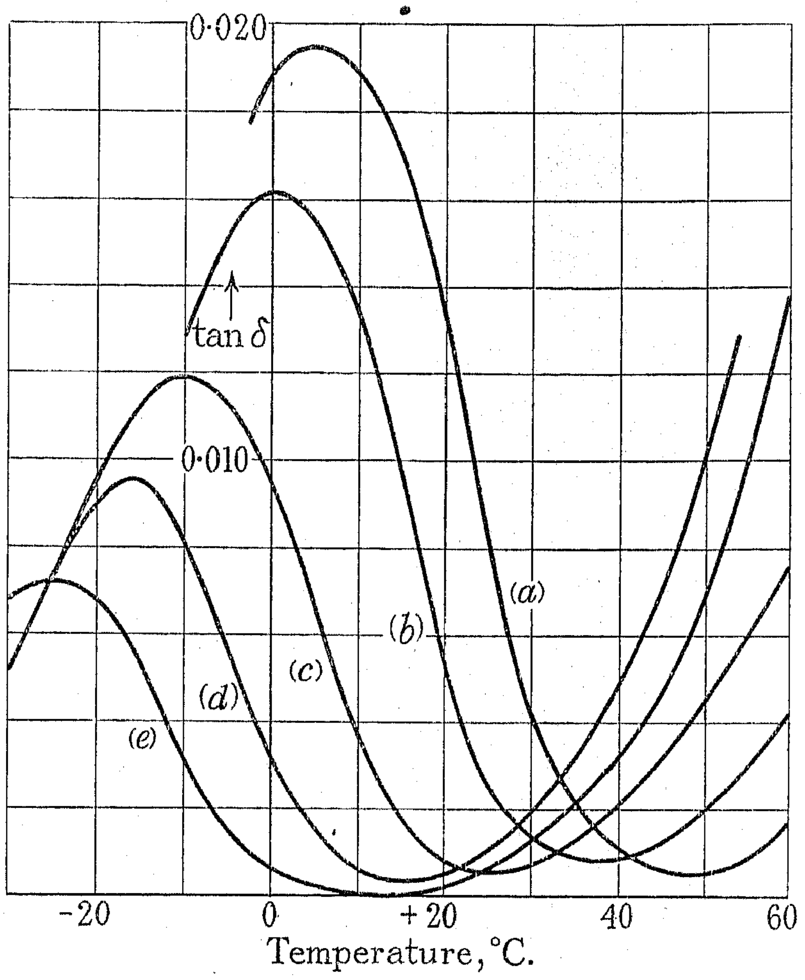

FIG. 12.—Bormann and Gemant: cylinder oil and resin mixtures (frequency = 50).

Resin content: (a) = 50 per cent; (b) = 40 per cent; (c) = 25 per cent; (d) = 10 per cent; (e) = nil.

In 50-cycle measurements on a cylinder oil regarded as particularly free from polar molecules, Bormann and Gemant‡ obtained power-factor (tan δ) variations with temperature similar to those recorded by the several previously-mentioned authors. The effect of adding different amounts of a viscous polar material—resin—to this oil is shown in Fig. 12. It is seen that the loss maximum is increased and displaced to higher temperatures with greater resin content. The conductivity of the mixture at a given temperature, as shown by the loss-angle values in the high-temperature range where the component of loss arising from conduction predominates, decreases owing to the increased viscosity produced by the resin additions. The Debye theory would require the dipole content of the cylinder oil to be equivalent to that of about 30 per cent resin, a value which was thought to be highly improbable. On the other hand, inhomogeneities in structure arising from impurity, which were affected by the addition of resin, were observed in micro-photographic studies of the oil, and these provide the basis on which the loss variations are explained. At the same time, it is remarked that the possible importance of a polarization effect arising from the displacement of charged particles is not to be excluded, although this is not developed. From the fact that curve (*e*) (Fig. 12) for the cylinder oil alone ranges perfectly with the curves obtained for the oil-resin mixtures, it is suggested that the resin dipoles are not directly responsible for loss, but operate indirectly by influencing the viscosity of the mixture, and consequently the conductivity of the original constituents. On heating the cylinder oil in air its physical structure became more irregular and the losses increased, although the temperature at which the power-factor maximum appeared remained unaltered.

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* See Bibliography, (40). Ibid., (57).

* See Bibliography, (58). † Ibid., (59). ‡ Ibid., (60).

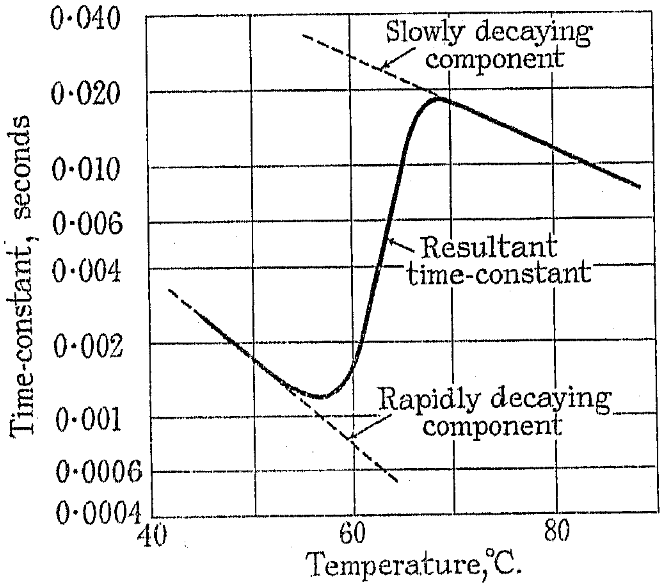

FIG. 13.—Whitehead: pure resin.

Further evidence against the importance of dipole orientation in these measurements (50 cycles per sec.) is claimed from the fact that similar changes in behaviour resulted on the addition of polar and non-polar liquids—chlorbenzene and hexane respectively—to the cylinder oil. (This test is hardly convincing, however, because of the rather small molecular dimensions of the added material.) Also, the addition of a small percentage of paraffin to a transformer oil which showed a power-factor maximum at about the same temperature (25° C.) as the more viscous cylinder oil, reduced the loss in this region enormously, although the paraffin had separated out as a solid structure leaving the viscosity of the liquid part sensibly unchanged.

Short-time studies of the charge and discharge currents in a pure resin under d.c. voltage have been carried out by Whitehead.* Two principal components were observed in the discharge current, one decaying rapidly and the other slowly, leading to two types of relaxation times. The variation and relative importance at different temperatures of these two time-constants are shown in Fig. 13. The component of smaller time-constant is the principal factor in determining the dielectric loss at low temperatures, when the resin is highly viscous, but gives place to the other component in the region of 60° C. The ratio of the time-constants at this temperature is about 30. Interpretation of the above action on the basis of the Debye theory would indicate that two polarized particles are involved, the ratio of their radii being roughly 1 : 3. Whitehead suggests, however, that the slower type of absorption is associated with the separation of space charges due to the viscous displacement of some type of large slow-moving ion or charged colloidal particle in a process of restricted conduction. It is significant that the component of loss and power factor due to this slow component of time-constant increased rapidly with increasing temperature, and merged finally into a loss due to simple conduction. The more rapidly decaying component apparent in the low-temperature range is regarded as arising from an irregular solidification, resulting in a combination of conducting channels and non-conducting solid portions. Along with the observed variation of power factor and dielectric constant at 50 cycles per sec. in this region of temperature, it can be explained, therefore, in terms of the Maxwell–Wagner theory.

ACKNOWLEDGMENTS.

The author's thanks are due to Mr. R. S. Eaton, M.A., of the College of Technology, Manchester, for his valuable assistance during the translation of the German script referred to in the paper.

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SOME MEASUREMENTS ON THE ELECTRICAL CHARACTERISTICS OF INSULATOR STRINGS.*

By W. G. Standring, M.A.

[From the National Physical Laboratory.]

(*Paper first received* 27*th June, and in final form* 18*th November,* 1932.)

Summary.

Outdoor measurements of power factor and impedance on various types of insulator strings are described and the results summarized. The best shape of insulator for unfavourable atmospheric conditions is discussed, and suggestions are made for further research.

Introduction.

The work was carried out during the winter of 1930–31 for the Central Electricity Board at the Dalmarnock substation, with the object of determining the best type of insulator for use in industrial areas. It was considered that the results indicated the most favourable lines on which to conduct a research and that further work would lead to definite knowledge of the necessities of insulator design for service in bad conditions with the minimum of attention. Unfortunately it has not been possible to continue the work. Inquiries have, however, been received concerning the nature of the results, and it is possible that this paper may be found useful, not as a conclusive guide to the best type of insulator, but as suggesting fruitful lines of experiment.

The characteristics measured were power factor and impedance, not flash-over, the voltage available being insufficient for the flash-over of complete strings. It is considered that actual flash-over values of complete strings are necessary to enable one to pronounce judgment on the relative merits of different types of insulators. Considerable information has, however, been obtained. In severe fog and frost a deposit grows until the surface resistance of a string is reduced to some 2 megohms, and it is possible that the leakage current associated with such low values is the primary cause of breakdown. R. J. C. Wood† gives as a criterion of breakdown the surface resistance calculated for a uniform deposit on exposed surfaces. It seems possible that the resistance measured under conditions at which flash-over is likely to occur may be more relevant.

Significance of Power Factor and Impedance of an Insulator String.

Preliminary measurements at Teddington on some fouled insulators removed from a line in the Glasgow area appeared to indicate a clear correspondence between power factor and flash-over voltage, and it seemed likely that a useful empirical relation might be found. Subsequent experiments, however, showed that the flash-over voltage depends on the distribution of the deposit. A highly conducting deposit on the top and bottom of a disc insulator with a narrow gap at the rim of the disc gives a low flash-over voltage and a low power factor. On the other hand a continuous uniform deposit may give a power factor of 0·9 without lowering the flash-over voltage appreciably below the clean dry value.

Measurements of power factor and impedance may, however, afford useful information of the growth of deposit on insulators. Fig. 1 represents diagrammatically a fouled suspension insulator. C_1 is the capacitance when clean; C_2 and R represent the condenser with resistance in its plates formed by the outer and inner layers of deposit; and S is the surface resistance between inner and outer layers. Observation shows that the least deposit occurs on exposed vertical surfaces, so that in the early stages of surface contamination the inner and the outer layers of deposit may be electrically separated. If the resistance S remains sufficiently high, the capacitance of the fouled unit increases—as R decreases through contamination—towards the limit $C_1 + C_2$, and the power factor $\cos\theta$, where

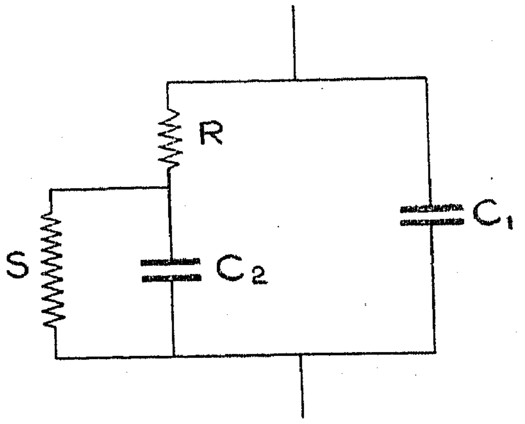

Fig. 1.—Diagrammatic representation of fouled insulator.

C_1 = capacitance between cap and pin; C_2 = capacitance between outer and inner layers of deposit; R = equivalent resistance in series with C_2 to allow for resistance of deposit; S = resistance of deposit on vertical surface of unit.

$$\theta = \text{arc tan}\left(RC_1\omega + \frac{C_1 + C_2}{RC_2^2\omega}\right)$$

first increases and then decreases. If S does not remain so high, the power factor is given by a more complicated expression. There may be no decrease in power factor, and R and S may drop low enough to make the power factor practically unity and the effect of C_1 and C_2 negligible. Measurements such as those described in this paper will give an idea of the relative magnitudes of C_1, C_2, R, and S; and such information about the distribution of the deposit may provide a useful indication of the cause of breakdown.

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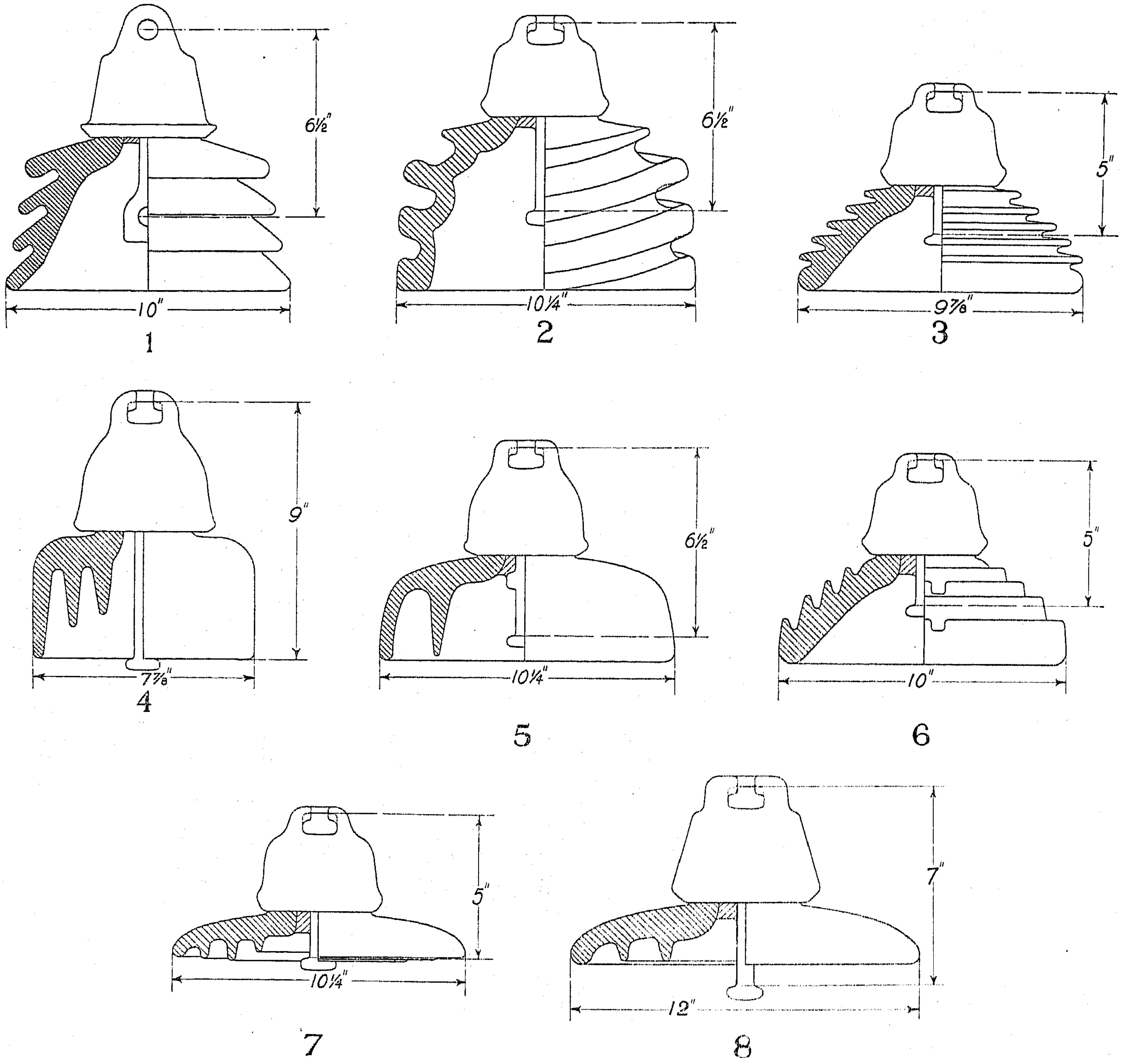

Fig. 2.—Insulator types tested.

Tests Carried out at Dalmarnock.

Measurements of power factor and impedance were made during January and February, 1931, on 22 strings of insulators suspended from a test tower at Dalmarnock substation. The measuring circuit is described in the Appendix. One string of Pyrex* insulators of standard disc type was hung up clean, shortly before the measurements began. The others had been hanging unexcited and uncleaned since August, 1930, and consisted of the types illustrated in Fig. 2. They comprised 7 strings of 8 units of type 1, 2 strings of 7 units of type 2, 2 strings of 10 units of type 3, 1 string of 6 units of type 4, 2 strings of 8 units of type 5, 2 strings of 10 units of type 6, 1 string of 10 units of type 7 (discs 10 in. diameter), 2 strings of 8 units of type 8 (discs 12 in. diameter), and 2 strings of 10 units (2 discs 12 in. diameter and 8 discs 10 in. diameter).

Measurements were obtained in fine weather, in rain, and in fog and frost, the combination of fog and frost representing the most unfavourable condition. No actual flash-over was obtained, the voltage of the test transformer (85 000 volts) being insufficient to produce flash-over under the worst conditions experienced. A brief period of fog occurred about the 5th January, 1931, at the beginning of the tests. Later, 8 strings of different types were brought down from the tower and were mounted on a ground framework for ease and rapidity of operation, as it was intended, in later fog periods, to reduce the number of units in the strings until it was possible to obtain a flash-over with the voltage available, and to compare the performance of different types. Unfortunately no more fog was experienced; but the results obtained from the measurements do afford some information about the behaviour of the different designs of insulators.

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* Pyrex electrical resistant glass.

Some flash-over tests in snow and in rain were made. The results are interesting, and indicate that different considerations should enter into the design of insulators for rain and for fog. With only one design, however, was it possible to cause flash-over, using more than two units, with the 85 kV available, so that trouble from snow or rain does not appear likely at Dalmarnock.

RESULTS OF THE MEASUREMENTS AT DALMARNOCK.

Variability of Results.

In any but the worst conditions of fog and frost the measurements yield little definite information about the comparative behaviour of the various types of insulators.

TABLE 1

Variation of Power Factor and Capacitance with Humidity.

Type of insulator (see Fig. 2) and number of units	Relative humidity = 57 per cent		Relative humidity = 85 per cent	
	Power factor	Capacitance	Power factor	Capacitance
		μμF		μμF
1 (8)	0·15	7·5	0·66	10
1 (8)	0·09	8·5	0·48	14
2 (7)	0·13	7	0·41	12·5
2 (7)	0·12	7·5	0·46	11·5
3 (10)	0·10	7	0·54	18
3 (10)	0·14	6	0·52	15·5
4 (6)	0·15	7·5	0·34	12
5 (8)	0·10	8·5	0·63	13
5 (8)	0·07	8	0·60	13
6 (10)	0·13	7	0·55	15·5
6 (10)	0·14	6	0·53	15
7 (10)	0·05	7	0·66	14

Different strings of the same type do not maintain a definite relation to one another as regards power factor, capacitance, or resistance, as illustrated in Table 3. Further, there is no definite relation between power factor and capacitance or resistance for any one string.

The variations with voltage given in Table 4 are also indefinite. Neither the greatest variations, nor the direction of the change, is associated with one type more than another, nor with the strings of which half the units were short-circuited.

Rain may be expected to give variable results on account of the impermanence of the continuity of the water film, and in any other condition except complete wetness of a deposit the surface of an insulator probably consists of a chance mixture of conducting and insulating elements which may be expected to give indefinite and variable results.

Range of Variation of Power Factor and Impedance.

The first sign of contamination, or of damp weather increasing the conductivity of the deposit above its dry value, was an increase in capacitance and power factor. Table 1 illustrates the difference between two fine days of different relative humidities. The capacitance has increased $1\frac{1}{2}$ to $2\frac{1}{2}$ times in value with a change in humidity from 57 to 85 per cent, while the power factor has increased 3 to 10 times.

TABLE 2.

Resistances in Fog (Power Factors all over 0·95).

Type of insulator (see Fig. 2) and number of units	Resistance (megohms) at 5 kV		
	5 p.m., 5th Jan., 29° F., white fog	2 a.m., 6th Jan., 25° F.	11 a.m., 6th Jan., 23·5° F., black fog
1 (8)	48	17	7
1 (8)	32	15	7
1 (8)	75	25	9
1 (8)	97	28	8
1 (8)	65	23	10
1 (8)	47	21	7
1 (8)	55	25	9
2 (7)	44	12	7
2 (7)	34	10	6
3 (10)	46	14	9
3 (10)	37	15	9
4 (6)	51	15	10
5 (8)	35	6	3
5 (8)	30	6	4
6 (10)	27	6	3
6 (10)	16	5	3
7 (10 in. discs) (10)	23	7	2
7 (Pyrex) (10)	42	6	3
8 (12 in. discs) (8)	21	6	3
8 (8)	30	6	4
7 and 8 mixed (10)	26	7	4
7 and 8 mixed (10)	26	7	4

At a later stage of deposition the power factor becomes practically unity, indicating that the whole of the surface of the porcelain has become conducting. This condition has been observed in fog, and Table 2 gives three sets of observations illustrating the range and rate of variation. These measurements were made at a few kilovolts, as it was found that raising the voltage altered rapidly the condition of the insulators. Measurements had only just been commenced when the fog occurred, and as the deposit under examination had been collected on unexcited strings it was considered desirable

TABLE 3.

Characteristics of Two Strings of 12-in. Diameter Discs.

Date	Kilovolts	Power factor		C ($\mu\mu$F)		R (megohms)	
		String A	String B	String A	String B	String A	String B
5 Jan.	10	0·99	0·97	16·5	15·5	25	46
6 Jan.	5	1	1	*	*	3·5	4
7 Jan.	5	1	1	*	*	9	8
7 Jan.	85	0·55	0·60	15	15·5	330	275
13 Jan.	10	0·03	0·07	9	9	†	†
13 Jan.	85	0·04	0·08	9	9·5	†	†
16 Jan.	85	0·65	0·64	15	16	250	245
17 Jan.	85	0·42	0·27	14	14	550	900
22 Jan.	85	0·49	0·56	15	11	390	450
27 Jan.	85	0·45	0·44	18	14	340	425

* When the power factor was nearly unity the capacitance could not be measured with any accuracy.
† When the power factor was small the value of R, which was very high, could not be measured.

TABLE 4.

Variation of Power Factor with Voltage.

Type of insulator (see Fig. 2) and number of units	Power factor				Col. 4 minus Col. 2
	2nd February		3rd February		
	85 kV	Increase at 10 kV	85 kV	Increase at 10 kV	
1 (8)	0·27	− 0·02	0·23	− 0·04	− 0·02
1 (8)	0·22	+ 0·04	0·23	+ 0·06	+ 0·02
1 (8)	0·21	+ 0·02	0·20	0·00	− 0·02
1 (8)	0·16	− 0·07	0·20	− 0·07	0·00
1 (8)	0·17	− 0·03	0·17	− 0·03	0·00
*1 (4)	0·14	+ 0·01	0·20	+ 0·01	0·00
1 (8)	0·20	+ 0·03	0·20	+ 0·02	− 0·01
2 (7)	0·29	0·00	0·33	+ 0·05	+ 0·05
*2 (3)	0·21	+ 0·14	0·13	+ 0·12	− 0·02
3 (10)	0·28	+ 0·06	0·32	+ 0·06	0·00
3 (10)	0·16	− 0·02	0·19	− 0·03	− 0·01
*4 (3)	0·23	+ 0·11	0·13	+ 0·05	− 0·06
5 (8)	0·49	+ 0·05	0·33	+ 0·06	+ 0·01
*5 (4)	0·21	+ 0·02	0·21	0·00	− 0·02
6 (10)	0·43	+ 0·04	0·35	+ 0·05	+ 0·01
*6 (5)	0·29	+ 0·06	0·24	+ 0·10	+ 0·04
*7 (5)	0·33	+ 0·08	0·25	+ 0·02	− 0·06
8 (8)	0·36	0·00	0·33	− 0·08	− 0·08
*8 (4)	0·24	+ 0·08	0·22	+ 0·09	+ 0·01
7 and 8 mixed (10)	0·48	+ 0·12	0·40	+ 0·14	+ 0·02
7 and 8 mixed (10)	0·46	− 0·15	0·41	− 0·15	0·00

* At this period these strings had half their units short-circuited by wire, and the voltage was left on continuously in the hope of obtaining a flash-over.

to obtain as much information as possible without altering conditions by applying high voltages.

Effect of Rain on Impedance of Insulator Strings.

In rain the electrical characteristics of the strings were frequently too unsteady for bridge measurements to be made, except in the case of a string of six units of type 4 (Fig. 2), which was always remarkably steady. Some sets of fairly steady values are given in Table 5. It will be seen that the string of 10-in. discs (type 7) had as low an impedance at low voltage on the 8th January as in the black fog on the 6th January. On the 7th January, a dull day, its impedance was 4 megohms at low voltage, and 210 megohms at 85 kV. On the 7th January, however, most of the strings had considerably higher impedances than on the 6th, and later (when perhaps more of the deposit left by the fog had been washed off) the values were higher still. It appears that rain is a much less serious condition than fog, and the measurements in rain yield little comparative information concerning the various types of insulators except for the surprising steadiness of the type 4 referred to, which may be significant.

TABLE 5.

Measurements in Rain.

Type of insulator (see Fig. 2) and number of units	Resistance (megohms)			16th January at 85 kV	
	8th January		15th January	Resistance (megohms)	Power factor
	About 10 kV	About 85 kV	About 10 kV		
1 (8)	23	80	41	160	0·59
1 (8)	15	100	24	300	0·55
1 (8)	13	235	32	315	0·60
1 (8)	23	100	—	245	0·73
1 (8)	16	210	—	285	0·64
1 (8)	16	190	—	345	0·46
1 (8)	13	230	—	330	0·51
2 (7)	15	195	42	310	0·57
2 (7)	11	235	—	265	0·65
3 (10)	13	—	21	110	0·91
3 (10)	22	100	32	130	0·84
4 (6)	8	215	28	330	0·58
5 (8)	5	65	25	175	0·67
5 (8)	6	105	—	270	0·56
6 (10)	6	105	11	215	0·57
6 (10)	12	70	17	215	0·57
7 (10)	2	65	47	360	0·68
7 (Pyrex) (10)	7	—	—	145	0·64
8 (8)	11	185	20	250	0·65
8 (8)	5	230	—	245	0·64
7 and 8 (10)	5	290	19	310	0·75
7 and 8 (10)	6	350	—	107	0·94

Variation of Power Factor and Impedance with Voltage.

In general it appears that the results of the measurements did not vary a great deal with the voltage applied, except so far as the application of high voltage in bad weather such as fog rapidly altered the condition of the insulators. For example, in fog an impedance of 5 megohms measured at a few kilovolts rapidly rose to 60 megohms with the application of 85 kV for about a minute. Measured again immediately at low voltage the impedance was still 60 megohms, dropping after half an hour at low voltage to 20 megohms.

Sometimes in good conditions steady readings at 10 kV and 85 kV did not differ greatly, some strings having higher values of power factor at low voltage, and some lower, as illustrated in Table 4. The first phenomenon possibly illustrates the drying effect of high voltage, the second an effect of ionization causing an increased loss.

Where changes in steady values with change of voltage were large, most of the change was not instantaneous. In such cases the power factor was less at high voltage, presumably through a drying effect.

Flash-Over Tests in Snow and in Artificial Rain.

On the 3rd March snow had fallen overnight, and some had lodged an inch or two deep on the windward side of the insulators. Tests were made by flashing-over as many units as possible of the strings on the ground framework. The snow was melting and conditions changing rather rapidly, so that the results are incom-

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plete, but in a period during which the flash-over value on two 10-in. discs changed from 60 to 70 kV the readings given in Table 6 were obtained.

TABLE 6.

Flash-over in Snow.

Type of insulator (see Fig. 2)	Number of units	Kilovolts at flash-over	
		With snow	Dry
4	1	60	—
2	1	70	—
5	1	50	—
3, 6, and 7	2	70	—
—	1	40	80

Artificial-rain experiments were carried out on the 4th March. Falling water was sprayed on to the insulators from two roses 7 or 8 ft. from the string, in an attempt to repeat similar conditions on each string in turn. The quantity of water represented a rainfall of about 6 mm per minute, the conductivity being about 25 000 ohms per centimetre cube. The results are given in Table 7. From the successive figures for type 6 it will be seen that the flash-over voltage increased with time, probably because the heavy rain removed some of the soluble or conducting parts of the deposit. The first readings on each type, however, were taken as soon as the water-sprays had been adjusted, and can serve for comparison. In rain, the worst type is evidently type 6, for it was possible to flash-over three units of this kind. The water from one unit all ran off at one place, from a gate in the lowest rib, and formed a solid jet making contact with the next unit.

TABLE 7.

Flash-over in Artificial Rain.

Type of insulator (see Fig. 2)	Number of units	Kilovolts at flash-over
1	2	75
	1	50
2	2	75
	1	50
	2	Over 85
3	2	75
	1	45
4	2	75
	1	45
5	2	70
	1	40
6	2	55
	3	85
	1	45
	2	75
7	2	70
	1	40
8	2	70
	1	40

The results of these tests, especially the measurements in rain, show that in these circumstances the high vertical surface does not have the effect which it had in fog. The depth of the air-gap between units seems to be the determining factor in rain, all units except type 6 having much about the same flash-over value.

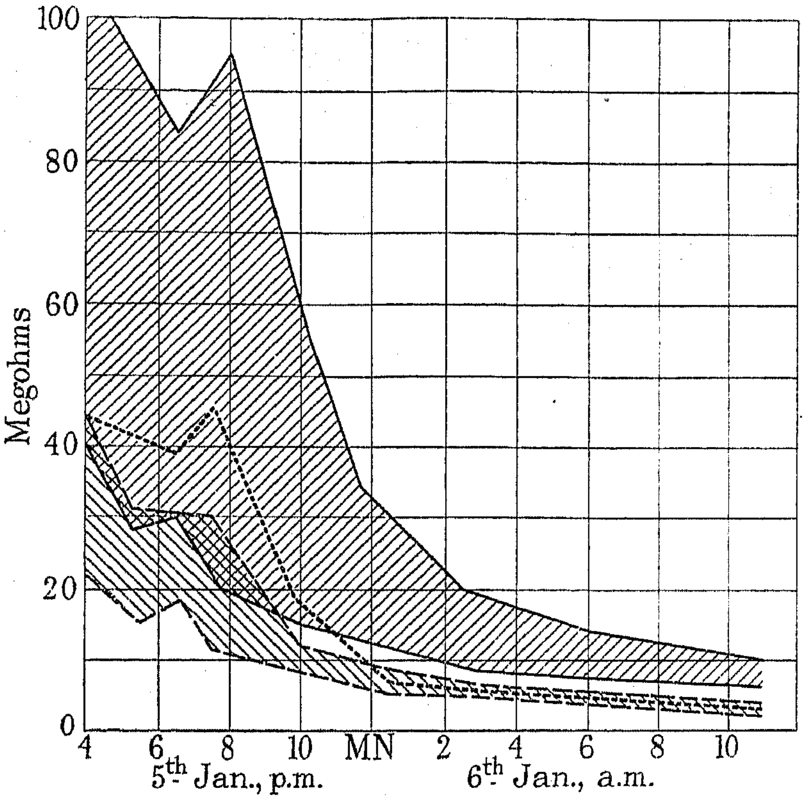

FIG. 3.—Results obtained under fog conditions.

▨ Types 1, 2, 3, and 4.

▧ Types 5, 6, 7, and 8, excepting Pyrex string.

- - - - - Pyrex string.

Influence of Shape of Insulators on Deposit and Impedance.

Differences between the various types of insulators were only clear in conditions of fog. In the worst condition the strings were separable into two groups; types 1, 2, 3, and 4 (Fig. 2), having resistances of 6 to 10 megohms, and types 5, 6, 7, and 8, having resistances of 2 to 4 megohms (at a few kilovolts). In Fig. 3 the full lines indicate the envelopes of the results of the first group, the broken lines the second group with the exception of the Pyrex string, which is indicated separately by a dotted line. In shape the group with the higher resistances may be described as having 4 or 5 inches of steep or vertical exposed face which will receive little deposit and be well washed. The other group contains disc insulators—type 6 (Fig. 2) which looks likely to collect deposit, and type 5, with 2 to $2\frac{1}{2}$ inches of vertical face.

Except for the discrepancy shown by type 5, which might have been expected to show slightly better results, it appears that the surface resistance in fog conditions is higher the greater the depth of steep or vertical outer surface on the insulator. Observation shows that rain washes effectively the upper surface of disc insulators; and measurements made during or after rain (e.g. those in Table 4) show that disc insulators may have comparatively high resistances. In the still air of a black fog, however, it may be that considerable deposition occurs on exposed horizontal surfaces, and that the vertical section plays the chief part in determining the surface resistance. If this is so, the resistance will also be probably greater the smaller the diameter of this vertical section. Further experiments in fog are required to demonstrate how far the flash-over voltage depends on surface resistance, and how far it is determined by the exposed vertical surface of the insulator.

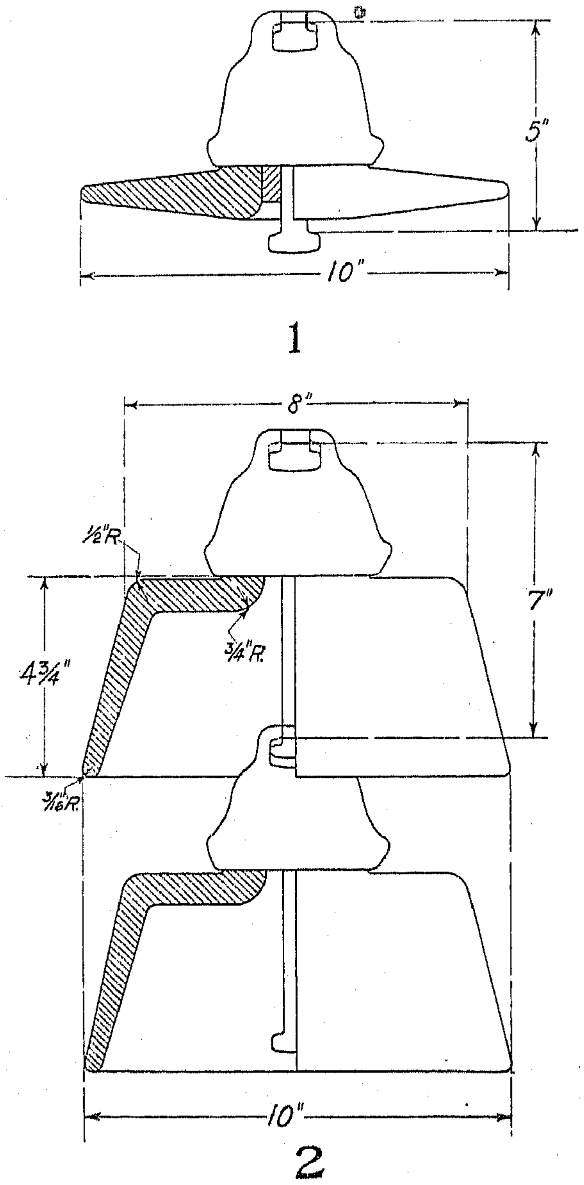

Fig. 4.—Suggested types of insulators.

The inside of vertical strings of insulators is not washed by rain, and observations agreed with those of Mr. P. J. Ryle, showing that all types became fouled, especially those with corrugations.* In developing insulators for use in fog with the idea of avoiding or reducing hand cleaning, it may be assumed that a hollow inside will certainly become fouled. The inside may therefore be shaped as simply as possible, and attention concentrated on the shape of the outside. From the measurements of surface resistance made in fog at Dalmarnock, it appears possible that corrugations on the outside may bring no advantage, the plain surface of the type 4 insulator having as high a resistance as any. It is felt, however, that further comparative measurements in fog are desirable, using more than one string of this type.

A disc insulator with a shallow under-surface without corrugations has been tried with success in Germany.* Tilted discs have also been used, but it may be noted that if these are not parallel, the air-gap, and therefore the flash-over in rain, may be much reduced.

In Fig. 4 two suggested types of insulators are illustrated which might be compared with standard types in a prolonged series of tests. The slightly convex under-side of type 1 will receive even less deposit during a black fog than the steep outer face of type 2, and may prove sufficiently exposed for wind and rain to prevent any deleterious growth of deposit with time.

Conclusions.

From the mass of data acquired during the tests described in this paper it is clear that comparisons based on a few measurements may be misleading. It is suggested that in experiments on insulator strings at least two of each type should be subjected to the same tests. Useful information seems only obtainable in the worst atmospheric conditions, because only then are the electrical characteristics of different types distinct.

The low value of resistance (Table 2) reached by the string of disc Pyrex insulators hung up clean just before the fog, throws doubt on the efficacy of cleaning as a protection against black fog.

So far as surface resistance is a criterion of safety, the experiments show that a deep vertical or steep exposed surface improves performance. It appears necessary to provide an exposed surface on which a heavy temporary deposit cannot settle in fog. Measurements, including flash-over on as many units as possible, made on some of the types in Fig. 2 and on the suggested types of Fig. 4, in all periods of fog during two or three successive winters without cleaning of the insulators, some being permanently excited at working voltage and some unexcited except for purposes of measurement, might lead to the development of a type of insulator which would require no cleaning in service.

The author is indebted to Dr. E. H. Rayner of the National Physical Laboratory for his constant interest and advice, to the staff at Dalmarnock for their ready assistance at all times, and to the Central Electricity Board for permission to publish an account of the work.

APPENDIX

Bridge Measurements.

The measuring circuit is illustrated in Fig. 5. Each string of insulators was supported from the tower cross-

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* P. J. Ryle: *Journal I.E.E.*, 1931, vol. 69, p. 805.

* *Elektrotechnische Zeitschrift*, 1931, vol. 52, p. 273.

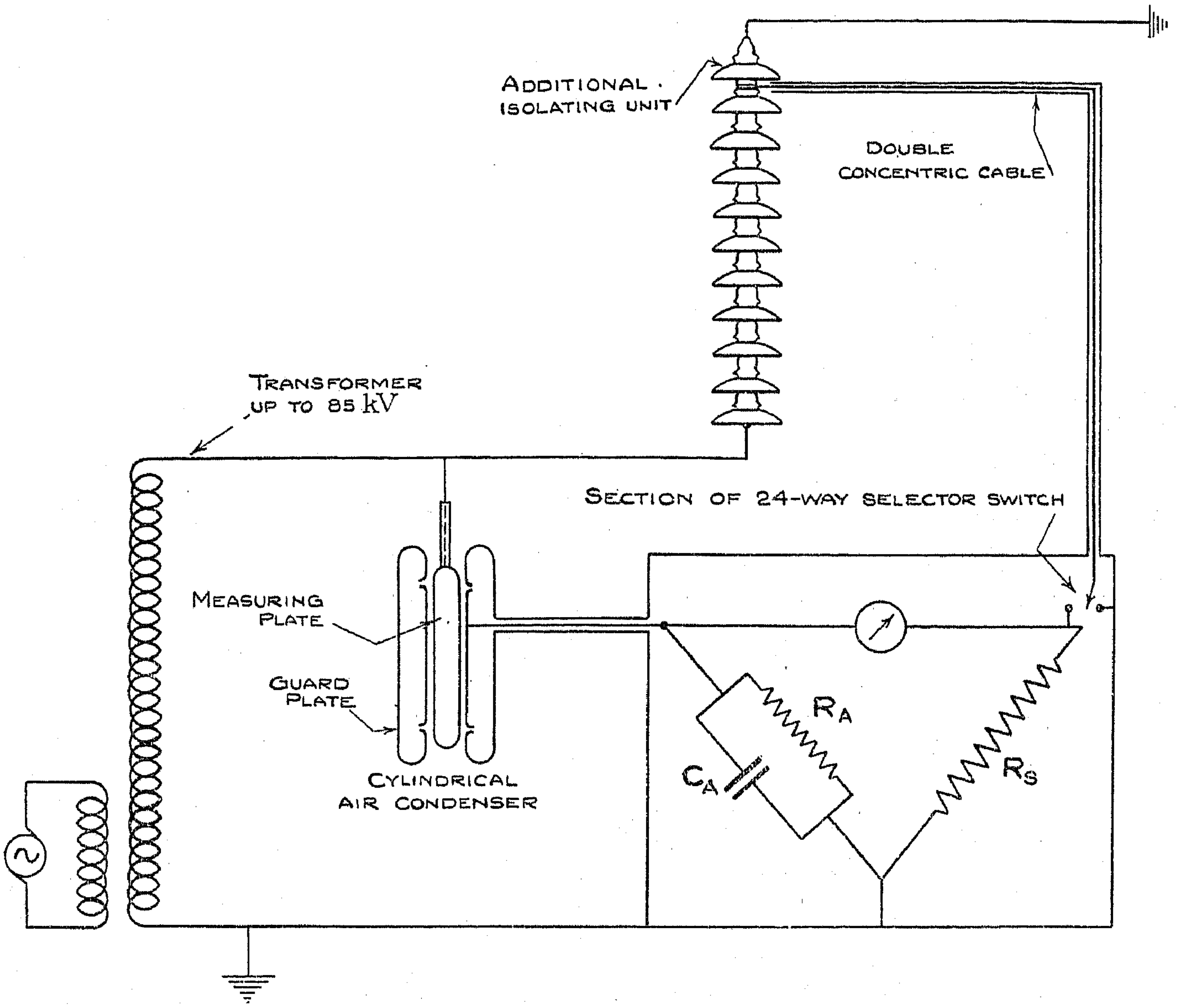

FIG. 5.—Diagram of measuring circuit (safety devices and automatic flash-over indicators omitted).

arm by an extra unit whose impedance, in parallel with the low-tension arm of the bridge, had negligible effect. From the top of the string itself a double concentric cable came down to a selector switch by which connection was made to the bridge or to earth. The outer conductor was used as an electrostatic shield. It was connected to earth, and correction was made for the capacitance of the cable which shunts the low-tension arm of the bridge. Where connection was made to the string the outer conductor was stripped back for 1½ in. and sealed over with rubber solution and manson tape, forming a weathertight covering. (It was found necessary to keep the unshielded portion of the central lead very short indeed.)

If the complex arrangement of resistances and capacitances in the string of insulators be represented by an equivalent arrangement of a capacitance C and a resistance R in parallel, then C and R are given by the following expressions:—

$$C = \frac{R_A K}{R_S(1 + R_A^2 C_A^2 \omega^2)}$$

$$R = \frac{R_S C_S}{K} \cdot \frac{(1 + R_A^2 C_A^2 \omega^2)}{R_A^2 C_A^2 \omega^2}$$

where K = capacitance of the loss-free standard air condenser,
R_S = bridge resistance in series with string,
R_A = bridge resistance in series with standard air condenser,
C_A = capacitance in parallel with R_A,
and $\omega = 2\pi \times$ frequency.

Figures given in the tables refer to this equivalent arrangement of C and R in parallel. The power factor of the string is given by cos (arc cot $R_A C_A \omega$).

DISCUSSION ON

"THE LOWER-VOLTAGE SECTIONS OF THE BRITISH GRID SYSTEM."*

WEST WALES (SWANSEA) SUB-CENTRE, AT SWANSEA, 14TH DECEMBER, 1933.

Mr. C. G. Richards: On page 110 (vol. 74) the factor of safety of line conductors is given as 2 under the conditions of storm laid down by the Electricity Commissioners. This is in accordance with clause 12 of El.C. 53, but is the author satisfied with this factor of safety for steel-cored aluminium conductors in districts having a sulphurous atmosphere and near the sea coast? I note that careful electrical and mechanical tests are made on all apparatus, but I can think of no tests which will reveal the extent of the corrosion of the steel core in the above conditions. In my judgment, corrosion caused by a sulphurous atmosphere, particularly near the sea coast, will reduce the mechanical strength to a point where a factor of safety of 2 under the worst conditions of storm will be too low, long before the line will have reached the end of its life upon which capital repayments are calculated. I am surprised at the route chosen for the main grid lines in our districts, and I hope that the lower-voltage sections will be carried over safer routes. I think that unless additional capital expenditure made it prohibitive (and I hardly think it would have) the routes chosen should have been along, and within easy walking distance of, the mountain roads. We have in this district in winter time experience of storms which would make some of the pylons totally inaccessible for days together, at all times of the day as well as during the hours of darkness. As regards cables (page 199), in a paper recently read before this Sub-Centre it was stated that 132-kV cables had been taken out of service in certain parts of the U.S.A. owing to the high dielectric losses sustained in their operation. In view of this it would be instructive if the author could describe the Board's experience with respect to dielectric losses in cables. We are familiar with corona effects in certain weather conditions on overhead lines at lower voltages than 66 and 33 kV; I should like to know whether corona effects are observable and, if so, under what conditions and with what results upon the operation of the lines. I should like to ask the author why it was not thought necessary to adopt on-load ratio-changing for transformers under 2 000 kVA. I can find no reference in the paper to the Board's method of protection against failure of the insulation between 66-kV and 33-kV windings, particularly where transformers are being operated with insulated neutrals. In my own experience I have come across a case where the fitting of an earthed metal barrier between windings prevented a serious breakdown. An account appeared in the daily Press last August of a serious accident in the South of France as the result of the failure of the insulation between the primary and secondary turns of a transformer, in consequence of which the low-voltage system became charged to an extra-high voltage. The sudden rise in voltage caused several people to rush to their switches for the purpose of switching off the current, and as a result two householders were killed and many injured. Several meters exploded, and some small fires occurred. With regard to the earthed guards used at road crossings, it appeared to me—in looking at some of these guards from the ground—that if a breakage occurred live conductors would make contact with anything above ground level before touching the earthed metal guard. In particular, when this Sub-Centre visited the Tir John North site I noticed these conditions at a roadway crossing nearby. Before concluding, I should like to touch upon one commercial point. The Electricity Commissioners' statistics for the years immediately preceding the preparation of the South Wales and South-West England scheme show that the number of units sold by authorized undertakers in South Wales equalled or exceeded the number of units sold in the South-West England part of the area. Further, in the South Wales area we have, in proportion to our acreage and population, more private plants for industrial purposes than any single electricity district in Britain. With these conditions in mind I am at a loss to understand why the South Wales and South-West England scheme as originally published provided for such heavy capital expenditure in South-West England as compared with South Wales, where there appeared to be such a ripe field for the lower-voltage sections of a national grid.

Mr. A. Jarratt: Has any bird trouble been experienced on the 33-kV pin-type insulator line? What is the estimated life of the galvanized steel-cored aluminium? An atmosphere laden with acid and salt will soon attack the galvanized steel, owing to the "breathing" of the aluminium when the temperature alters. Also, what types of surge absorbers have been tried out on the 33-kV lines?

Mr. G. O. James: Table 5 shows that not only are oil-filled cables cheaper to install than the solid-dielectric type but their current rating is considerably higher. I read some time ago that certain sections of an oil-filled cable system in Chicago were removed from service, not because the system had failed, but because the dielectric losses had become too great for economic working. Could the author give a comparison of the dielectric losses, expressed as a percentage of the I^2R losses of the solid-dielectric and oil-filled cables respectively, discussed in Table 5? I am surprised that the C.E.B. have not adopted the pilotless carrier-current system of protection for their overhead lines. There appears to be a wide field of application for this type of protection, the simplicity of which is a great advantage. I am also surprised that thermionic valves have not gained a wider popularity on the grid system, as they are much faster in action than mechanical devices such as relays.

[The author's reply to this discussion will be found on page 121.]

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* Paper by Mr. C. W. MARSHALL (see vol. 74, p. 105).

Western Centre, at Gloucester, 16th April, 1934.

Dr. J. L. Miller: The author's remark that surge absorbers or cables are used for surge protective purposes on the grid lines in exposed positions raises interesting points, and perhaps some comments on the manner in which cables give this protection may be of value. Essentially a cable by virtue of the internal to-and-fro reflections flattens the front of an incoming wave (so decreasing the inter-turn stress in the connected transformer), but does not reduce the voltage amplitude. Suppose an incoming wave of voltage E and having an infinitely steep front is travelling towards a cable of length l and surge impedance Z_c on a line of surge impedance Z_l, a transformer being connected to the end of the cable. When the wave meets the junction the voltage in the cable is $2EZ_c/(Z_l + Z_c)$, and this voltage is doubled on reaching the transformer. A reflected wave of voltage $2EZ_c/(Z_l + Z_c)$ travels back to the junction, and this wave is in part re-reflected to a value of $2EZ_c(Z_l - Z_c)/(Z_l + Z_c)^2$. Thus, $2l/v$ seconds later (v being the propagation velocity in the cable), the terminal voltage is increased from $4EZ_c/(Z_l + Z_c)$ to $8EZ_cZ_l/(Z_l + Z_c)^2$. Further reflections take place until the final voltage of $2E$ is attained, but the effect of reflection is to make this voltage increase in a series of steps, so that the front of the wave is effectively flattened. Since the surge impedances of lines and cables can be calculated, this flattening can be estimated with good accuracy. In practice, losses and the transformer capacitance will round off the steps. The losses will also, of course, give some reduction in the height of the steps, but in general, with the infinitely long wave used in the above argument, there will not be much reduction in the final voltage of $2E$. In practice, however, the dangerous waves usually have short backs, and therefore if the cable is reasonably long the final voltage of $2E$ will not be attained. This, coupled with the front flattening that occurs, indicates that cables, if of sufficient length, afford useful protection. The above arguments make it evident, also, that the short lengths of cable sometimes used to join low-voltage lines at road crossings, for instance, have no appreciable value in modifying the shapes of waves. If earth wires on towers are to be effective, low values of the tower-footing resistance are required. It would be interesting, therefore, if the author could give some idea of the order of magnitude of the footing resistances attained on the grid lines.

Mr. L. F. Driscoll: I should be glad if the author would state precisely what happens, and the procedure to be followed, when one or more of the high-tension grid lines break. Is the section immediately and automatically isolated on each side of the break, and is the faulty section patrolled on each side of the break before any attempt is made to reclose the circuit breakers so as to re-energize the lines? What provision is made for ensuring that the broken conductor is dead and discharged to earth so far as line capacitance effects are concerned? Again, it would appear possible for a conductor to part from the point of suspension on either or both sides of a road or rail crossing without making earth contact, and thereby form a very dangerous obstruction. Should not all such crossings, regardless of the factor of safety for mechanical strength, be provided with earth guards?

Mr. Arthur Ellis: On the lower-voltage sections of the grid there are 1 540 miles of mains, 185 substations, and transformers rated at nearly $2\frac{1}{2}$ million kVA. What additional cost (if any) has been involved in the provision of these lower-voltage sections, over and above the cost of the scheme contemplated originally by the Commissioners and included in the estimate referred to in the 1926 Act? I note that it has been necessary to use circuits having capacities ranging from 40 000 to 1 500 kVA, and with transformer capacities ranging from 45 000 to 50 kVA. I suppose that, in those cases where the larger size mentioned is used, the Board receive their supplies from more than one source. I should be interested to have the author's opinion as to the use of steel-cored aluminium conductors compared with the use of cadmium-copper. What is his opinion of the type of conductor built up of interlocked strands in regard to cost compared with that of the ordinary type of line conductor, service, and other conditions which have to be applied to its use? I am equally interested in his references to the use of Buchholz alarms and to vibration dampers. In connection with the scheme in which I have recently been interested, dealing with a supply of considerable magnitude to an important industrial concern, I have used both of these in order to secure greater reliability of supply. Vibration dampers have been used in conjunction with considerably modified conditions relating to the sagging and tension of the line conductors; in my opinion the more general use of higher tensions has been the cause of the conductor troubles so far experienced. I note that, in the Scottish part of the scheme, pin insulators have been used; and I should like to know whether, in this case, efficiency and reliability have to any extent been sacrificed for the sake of economy in the cost of construction. I should also like to have some information as to the use of 66-kV oil-filled cables, more particularly in those cases where such cables happen to be operating under loaded conditions. Have any troubles been encountered due to parallelism of grid conductors, and, if so, how have they been dealt with? The prices of transformers shown in Table 7 are very interesting, but I doubt very much whether similar prices will be available for future requirements, because it would seem that the manufacturers have created very keen competition amongst themselves in order to secure work from the Board. I have often wondered whether, and to what extent, this has meant the sacrifice of efficiency in design and construction. In connection with the supply to the industrial concern to which I have referred, very great care has been paid to the question of earthing.

Mr. W. Hill: I should like to extend the question asked by Mr. Ellis, and inquire whether the use of cadmium-copper and copper lines is not being considered, in view of the very slight extra cost (see Table 4) and the disadvantages of using steel-cored aluminium, particularly when maintenance is required. Referring again to Table 4, I note that the "other items" cost of the single-circuit 33-kV lines varies from 12·7 to 2·6 per cent. Surely the size of conductor does not account for this difference. Furthermore, in the case of 11-kV lines only £5 per mile is allowed under "Other Items." Surely this very low figure cannot be intended to cover all tree-felling and cabling of Post Office lines. I note that the 11-kV lines were erected without earth wires; can satisfactory switch operation and discrimination be arranged in these circumstances? With regard to the earth plates, I should be interested to know what resistance values have been obtained, because when using a similar size of earth plate considerable trouble has been experienced in maintaining satisfactory earth values. My experience tends to show that an earth plate may be satisfactory for a year or two and then cease to be efficient, particularly after it has been called upon to carry current under service conditions. With regard to the bushings, for both transformers and switchgear, I should be much obliged if the author would give some indication of his preference after the experience he has obtained. Maintenance costs on oil-filled bushings appear to be very high.

Mr. A. Nichols Moore: Whilst I appreciate that as yet there has been little opportunity to form an opinion on the effectiveness of the design and operating conditions of the lower-voltage sections of the grid, the author may perhaps be able to give me some information upon the following points. For instance, to what extent has the automatic operation of transformer cooling apparatus proved reliable in practice, and have the Board experienced any serious trouble in regard to transformer noise? I recently visited several of the more important grid substations in the South-West England and South Wales area, and, with one or two exceptions, was struck by the almost complete absence of noise from the transformers.

Another point is as to the effectiveness of earthing of the transmission line. Has any system of periodic testing been adopted, and what results are being obtained? I understand that in some cases there has been considerable difficulty in ensuring effective earthing.

In regard to the life of the poles, I should certainly suppose that, in the long run, steel must prove most suitable.

Another very important consideration is as to the various types of switchgear adopted by the Board for substation operations, more particularly in respect of isolating and tap-changing. As a result of the experience so far obtained, has the author been able to form an opinion as to whether any particular type is to be preferred?

Here I should like to mention the question of switchgear tests. With switchgear for which I have been personally responsible I have always insisted upon very complete tests, more particularly full-load current tests, being carried out at the manufacturer's works. These tests are very essential, as they have occasionally disclosed serious defects (particularly in workmanship and fitting) which could not have been disclosed under running conditions; for it should be borne in mind that frequently the specified current capacity of a particular equipment may never be reached, or at any rate not until the equipment has been in commission for a period of, say, one or two years. The fact that the defects were disclosed at the manufacturer's works enabled them to be dealt with and eliminated without difficulty, whereas this could not have been done conveniently if at all after erection of the switchgear on site. Have the Board insisted in their specifications upon the carrying out of such tests?

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT SWANSEA AND GLOUCESTER.

Mr. C. W. Marshall (*in reply*): Mr. Richards is of the opinion that corrosion caused by a sulphurous atmosphere, particularly near the sea coast, will reduce the mechanical strength of steel-cored aluminium conductors to a point where the factor of safety of 2 under the worst storm conditions will not be attained. He should, however, note that the control tests which are being made include complete dissection of the conductor samples. Such samples which have been taken from lines in use for 5 years show no signs of dangerous corrosion.

The Board's experience with 66-kV oil-filled and solid-type cables, which now extends to some 4 years of service, has not revealed any sign of deterioration similar to that which has been reported as taking place on 132-kV cables in the United States.

Corona effects are observable on low-voltage lines only during periods of fog. They have, in a few instances, given rise to flash-over of the insulators, but trouble of this type has not been extensive.

In the early stages of the Board's activities the cost of on-load ratio-changing equipment for transformers was so high that it was not considered justifiable to fit such equipment on transformers of less than 2 000-kVA capacity.

The balanced leakage protective equipment used by the Board would effectively clear faults between 66-kV and 33-kV windings. It has been the Board's standard practice to have a neutral on one or other of the windings earthed in all cases.

The design of earth guards at road crossings has always been, and remains, a controversial matter. The type generally used up to the present, while far from ideal, at least serves to earth the conductor with certainty in the event of a failure of the supporting insulator.

The point raised by Mr. Richards regarding routes of lines and the relative expenditure on lines in South-West England and South Wales does not come within the scope of the paper.

In reply to Mr. Jarratt, up to the present only two cases of line flash-over due to birds have been experienced on the Board's 33-kV pin-insulator lines. The estimated life of the steel-cored aluminium conductors is 25 years. The only type of surge absorber which has been installed on the Board's 33-kV lines is that made by Messrs. Ferranti.

It is not possible to give a complete answer to the query of Mr. James regarding dielectric losses in cables. The following typical figures taken from contract documents may, however, be of service to him. The guaranteed dielectric loss of a 3-core 33-kV 0·15-sq. in. solid cable at normal voltage is 1·34 kW per mile. That for a 66-kV 0·15-sq. in. single-core oil-filled cable at normal voltage is 4·8 kW per mile of 3-phase circuit. The temperature of reference in each case is 15° C.

Pilotless carrier-current systems of protection have many great advantages. They are, however, not particularly suitable for the relatively short lines used by the Board because of their high cost. Mr. James states that their simplicity is a great advantage, but I consider that they are complicated compared with the types actually employed.

The advantages of thermionic-valve relays from the standpoint of speed of operation are very evident, and I hope that protective-gear developments by British firms using such valves will not be long delayed.

Replying to Dr. Miller's inquiry, the tower footing resistances on the grid lines vary from a minimum of 5 ohms to a maximum of about 70 ohms.

I would inform Mr. Driscoll that in the event of conductor breakage the line section involved is immediately cleared by the circuit breakers at either end of the section. The fact that there is a fault on the line is indicated on the protective relays, and the circuit breakers are not reclosed until the line has been patrolled and the fault rectified.

Before work is done on the line it is isolated and earthed at each end, and is also earthed at the point of work. The danger which Mr. Driscoll envisages from conductors which have sagged abnormally, but which are not in contact with earth, cannot be wholly dismissed, but so far there does not seem to be any justification for providing special safeguards against it as the cost of such a provision would be out of proportion to the additional safety to be derived therefrom.

Mr. Ellis will be interested to learn that, with the exception of one 33-kV line in Central England, the lower-voltage sections of the grid are exactly as contemplated by the Commissioners. The larger-size transformers, such as those of 45 000 kVA capacity, used on the lower-voltage sections of the grid are in the London area, where the connections are virtually part of the main grid system.

The principal advantage of steel-cored aluminium conductors compared with cadmium-copper conductors lies in their lower cost.

Interlocked-strand conductors have, in my opinion, much to recommend them: they have advantages from the standpoint of minimizing corrosion, giving a complete protection to the steel core, and also have a smaller diameter for a given conductivity. As against this, however, there is the disadvantage of somewhat higher cost and possibly of greater liability to vibration.

The relative merits of pin and suspension insulators have already been dealt with in my reply to Mr. Kennedy.*

Up to the present, 66-kV oil-filled cables have given complete satisfaction, there having been no faults in any of the sections used by the Board. The loading, however, has not yet gone much beyond half the rated capacity of the cables.

Cases of interference with communication lines due to parallelism with grid conductors have been very few, and those which have occurred have, in all cases, been due to the use of earth-return communication circuits. The interference, if continuous, can be removed by using metallic returns and—if present only under fault conditions—by the use of discharge tubes.

In reply to Mr. Hill, there is at present no doubt of the Board's intention to adhere to the established standard of using steel-cored aluminium conductors.

The table of total costs of overhead lines exemplifies lines in widely different classes of the country, ranging from open moorland to comparatively densely populated industrial areas. Hence the somewhat wide difference between the costs.

The only 11-kV line erected by the Board is a spur line, and this can be satisfactorily protected by a combination of overload and earth-leakage devices.

The matter of earth resistance has already been touched on in my reply to Dr. Miller. It is recognized that the values obtained initially are not necessarily stable, and periodic tests will be carried out to determine what changes take place and what modifications are necessary to keep the resistance values low.

The experience of the Board shows that 66-kV condenser-type bushings are preferable to the purely oil-filled type from the standpoints of bulk and cost. At 33 kV the choice appears to lie between condenser bushings and those of the plain porcelain type.

The automatic operation of transformer cooling apparatus has, so far, proved quite satisfactory. Noise troubles have been confined to a very few cases of transformers in the immediate neighbourhood of dwelling houses. The transformers in South-West England and South Wales, to which Mr. Nichols Moore refers as being exceptionally silent, are of the low flux-density type.

Earth tests are carried out on all towers at which lightning flash-overs are experienced, and the results obtained do not indicate any necessity for more intensive testing.

Experience with switchgear and tap-changing equipment is not yet sufficiently extensive to justify a categorical statement as to the order of merit of different types.

Mr. Nichols Moore's experience in full-load testing at works is similar to that of the Board, and such type tests are always carried out before the gear goes into service.

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* See vol. 74, p. 264.

DISCUSSION ON
"ELECTROMAGNETIC PHENOMENA IN HIGH-VOLTAGE TESTING EQUIPMENT."*

FURTHER COMMUNICATION TO THE DISCUSSION.

Prof. H. Cotton (*communicated*): The author very rightly stresses the importance of voltage wave-form and a knowledge of the changes in wave-form with different conditions of operation. It is a comparatively simple matter to obtain a close approximation to a sine wave at full voltage, but with many methods of control there are considerable departures from this ideal form when the voltage is varied over a wide range. The disadvantages of the induction regulator have been discussed on several occasions, and the author points out that the variable-voltage single-phase alternator is more satisfactory than a constant-voltage alternator with any additional appliances of the type summarized on page 380. The main disadvantage of the variable-voltage alternator is that at very low excitations the wave-form on load may be considerably upset by armature reaction. This difficulty is overcome in a method of control which is being tried out at the present time in the Electrical Engineering Department at University College, Nottingham. The equipment consists of two single-phase alternators coupled together, and driven by the same motor, one of the alternators having a stator which is capable of rotation through 180 electrical degrees. Both alternators are excited to full voltage and their armatures are connected in series, as indicated in Fig. L. The method of control consists merely in rocking the stator until the vector sum of the two voltages is the value required for application to the transformer primary. It is obvious that by this method a range of voltage from zero to twice the voltage of one of the alternators is obtained without the necessity of making any adjustment whatever to the excitations. In Fig. L two transformers in series are shown, but this is unnecessary. The advantage of two transformers is that for comparatively low-voltage work each transformer can be supplied from one alternator, thereby giving two independent testing equipments. In this case voltage control can only be obtained by adjustment of the alternator excitation.

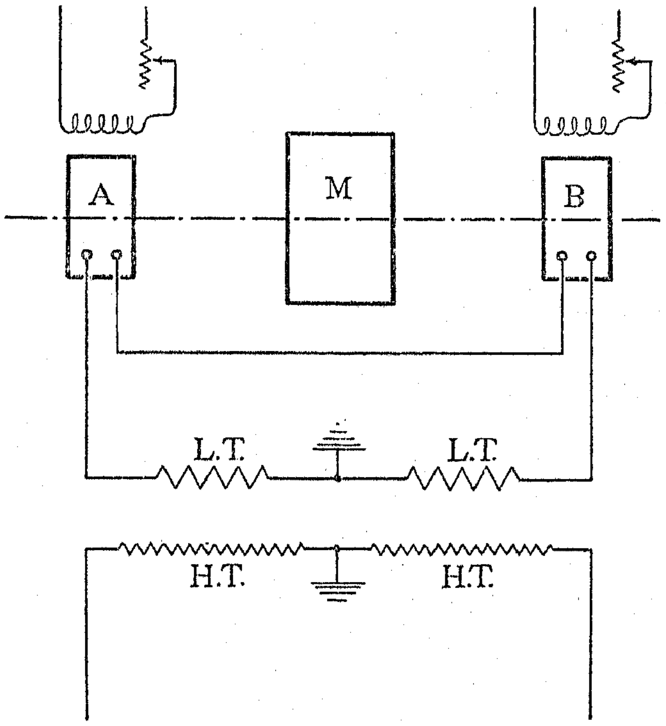

Fig. L.

M = driving motor.
A = alternator with fixed stator.
B = alternator with rotatable stator.

Mr. B. L. Goodlet (*in reply*): I am rather surprised that the scheme outlined by Prof. Cotton should appear to him to possess any advantages. Apart from an increased reactance, if the e.m.f. waves of his alternators contain any harmonics these will be brought into and out of phase as the stator is turned, with precisely the same kind of effect as that outlined in the paper for the induction regulator.

From the practical point of view the cost would appear to be prohibitive. Whereas several speakers state that alternators are altogether too expensive and Dr. Dunsheath uses one alternator to feed several transformers, Prof. Cotton would feed one transformer from two alternators!

In the paper it is recommended that the per unit synchronous reactance of a testing alternator should never exceed 0·75. This means that, at zero power factor (leading), about three-quarters of the air-gap flux is due to the armature reaction. There is no particular reason why this flux should not be practically sinusoidal, and a good designer will make it so by incorporating the design features mentioned on page 382. The equivalent load reactance can be varied by series-parallel transformer windings (see page 384). Making the stator phases in two halves which can be connected in series or in parallel gives additional flexibility at very small cost. These direct and practical methods are in my opinion preferable to any scheme of the kind suggested by Prof. Cotton.

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* Paper by Mr. B. L. Goodlet (see vol. 74, p. 377).

DISCUSSION ON

"AN ANALYSIS OF THE COSTS OF ELECTRICITY SUPPLY AND DISTRIBUTION IN GREAT BRITAIN, WITH SOME SUGGESTIONS AS TO THE CAUSES OF AND REMEDIES FOR THE SLOW RATE OF DEVELOPMENT."*

NORTH MIDLAND CENTRE, AT LEEDS, 7TH NOVEMBER, 1933.

Mr. E. A. Mills: I am entirely in agreement with the authors' conclusions. It appears to me inevitable that if the price of electricity is to be the minimum attainable the efficiency of distribution must be considerably improved and the number of tariffs and voltages appreciably reduced. I fail to see how this can be achieved unless some authority is set up to co-ordinate the distribution side of the industry. In recent years the rate of development has shown considerable improvement, but under present conditions the fullest use will not be made of the scheme derived as a result of co-ordinating the generating side of the industry. Many difficulties and prejudices would have to be overcome before an appropriate distribution authority could be set up, particularly in regard to local authorities who are the owners of gas and electricity undertakings. It is a mistaken policy to limit the activities of either gas or electricity undertakings; each should adopt a strong progressive policy with a view to increasing output as rapidly as possible without condemning the other's commodity. Neither gas nor electricity undertakings can afford to give the public a false impression of the value of their own particular commodity. The loss of revenue which has been sustained by many gas undertakings is due primarily to private enterprise absorbing the by-product business, partly to trade depression, and partly to competition with other forms of energy, including electricity. A combination of a gas undertaking with any electricity undertaking would not overcome this loss of revenue unless it was intended to fix prices—a policy which would never be accepted by the general public. Fig. L shows a comparison of the interest and sinking-fund charges of the gas and electricity undertakings of the Halifax Corporation, which was made some months ago for the purpose of illustrating the necessity for not limiting the activities of the electricity undertaking. A similar comparison might be made with advantage by many other authorities.

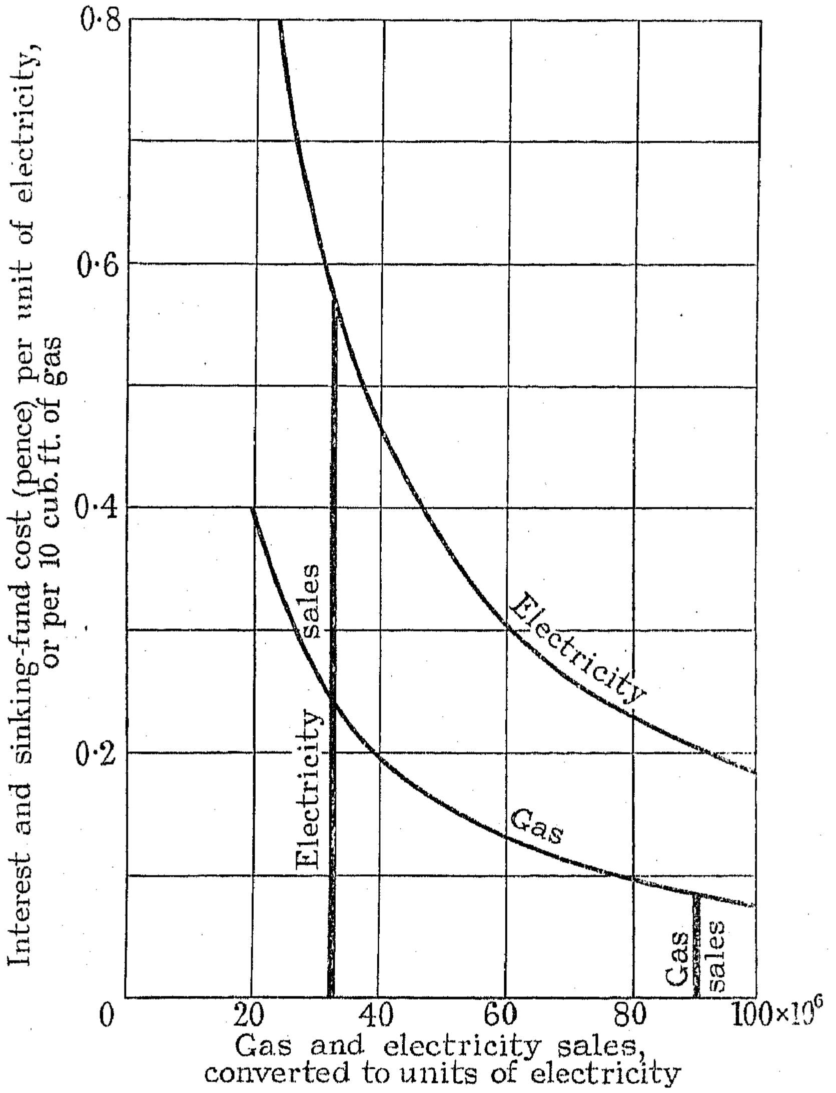

FIG. L.—Comparison of interest and sinking-fund charges for Halifax gas and electricity undertakings.

Mr. W. Dundas: The predominant impression obtained on reading the paper is that of a reproof for our shortcomings on the distribution side as compared with the laudable achievements in regard to generation. The very creditable results obtained by some of the undertakings specially mentioned by the authors are to no small extent dependent on the fact that they are of a highly residential nature. It would have been interesting to have had a comparison of some industrial districts which have suffered of late from trade depression, as it is very doubtful whether such good results would have been found in districts of this sort in spite of all the efforts of the engineer responsible for the developments. The question of distribution costs is of the utmost importance in these days of low and attractive tariffs, but how the latter are to be placed on a sound economic basis is often the subject of much controversy. To meet future developments capital is needed in advance, and it would appear that distribution costs must rise still higher before the benefits of increased sales compatible with expenditure will be realized. One of the present-day difficulties is the comparatively low voltage of the primary system of supply. The figure of 6·6 kV is much too low for many of the larger towns in which that voltage was originally adopted, and it must now be supplanted by a higher voltage. There is also the question of security of supply and the justifiable risks that may be taken in keeping down capital expenditure. On the other hand, one can pay too high a premium against failure of supply, and the choice at times becomes somewhat speculative. Some authorities adopt the practice of serving a large district on a single line. If domestic electrification is to be assured, however, surely it is to the interests of all concerned that more consideration should be given to reliability, for one can readily appreciate the temper of the housewife on repeated interruptions to the supply, and the adverse effect this will have on the development of the domestic load. The load curve shown in Fig. 14 appears to be exceptional inasmuch as it indicates a load factor of 50 per cent and gives a higher diversity factor than is usually obtained. The explanation is storage water-heating, which still remains undeveloped in this country. The load factor of an individual house consuming 6 000 units per annum is in the neighbourhood of 10 or 11 per cent. It is evident from the figures given in Table 6, in the column referring to repairs and maintenance, that other charges incidental to development have been included.

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* Paper by Mr. J. M. KENNEDY and Miss D. M. NOAKES (see vol. 73, p. 97.)

Mr. R. A. S. Thwaites: I propose to confine my observations to the final section, headed " Conclusions." We shall, I think, all be in agreement with the statement on page 113 that distribution powers over wide areas should be placed in the hands of single authorities. The only points on which there seems to be divergence of opinion are: (1) What is the ideal size of unit? and (2) How shall it be administered? The latest Statistical Returns published by the Electricity Commissioners show that in the year 1930–31 there were just over 4 million consumers being supplied in Great Britain. This number obviously could not be handled as one area. The authors suggest the possibility of the areas being coincident with those of the Central Electricity Board. I find that in the Mid-East England Area there are already more than 450 000 consumers, and some 550 000 additional premises unsupplied. The total number of potential consumers is therefore approximately 1 000 000, distributed over an area of 7 500 square miles. While it would be possible to administer supply to something between half a million and a million consumers in such an area, whether this could be done economically is another matter. The authors indicate that in some cases subdivision of these areas may be desirable, and if this suggestion were acted upon it might be that the concentrated loads in the large cities where the capital expenditure on the electricity undertakings exceeds, say, £1 000 000, might continue unaltered; this would account in the Mid-East England Area for 300 000 consumers, leaving approximately 150 000 consumers to be administered by a single authority. This is not an unwieldy number; the Leeds Corporation, for example, are already supplying more than 110 000 consumers. With regard to the question of the type of body which should administer such areas, it would be as well perhaps if we as engineers omitted this aspect of the problem from our discussions.

Mr. E. J. Evans: I should like to mention three points which emerge on a first reading of the paper. One is that the present large number of individual undertakings should be co-ordinated into a small number of larger area, and I should like to put forward a few statistical arguments in favour of this course. In Fig. 4 the authors have plotted the average revenue against the units sold per £ of distribution capital for all the undertakings in Great Britain, and drawn a phantom curve. The results obtained from the 40 small undertakings operated by Electrical Distribution of Yorkshire, Ltd., form a cluster of points lying considerably below the authors' curve, and if there is any relationship between them it is probably represented by a horizontal straight line corresponding to about 2·9d. per unit. The number of units sold per £ of distribution capital is only 12, and on the authors' curve this would correspond to 6½d. per unit. I therefore suggest that the effect of this principle of combining a number of small undertakings is to reduce the average cost to at most half of the figure obtained under individual operation. Similar deductions can be drawn from Fig. 6, where the revenue is plotted against the units sold per head of population. For the undertakings owned by Electrical Distribution of Yorkshire, Ltd., the average revenue of 2·9d. per unit and the average value of 25 units per head of population give a point which lies below the authors' curve and show the effect of amalgamation. My second point is that the authors' arguments in regard to the control of distribution are in some respects a little superficial. The Weir Committee estimated that in the year 1940 the average consumption of electricity would be 500 units per head of population, but if one plots the results for the past 10 years one finds that this figure will not be reached until 1951. Seeing that the Weir Report was published in 1924 that is an error of nearly 80 per cent. The Weir Committee also estimated that in 1940 the average price would be reduced to approximately 1½d. per unit, but this figure was reached in 1929. The lesson to be drawn from this is that one has to be very careful in making assumptions about the future. It is necessary to distinguish domestic supplies from power supplies when dealing with units sold per head of population. An undertaking supplying a large town which has a heavy industrial load may show a high consumption per head of the population, but if the purchasing power of the inhabitants is low the number of units sold for domestic purposes will be small. At first sight, however, the undertaking would appear to be quite efficient. Reverting to Fig. 6, if we plot the average revenue per head against the units sold per head we get a straight line; this line is likely to be rather misleading, as its obvious implication is that the sales of electricity are governed solely by the average price. My third point concerns Table 8. In presenting the paper the authors mentioned that a probable criticism would be the outgrowth of undertakings, and they immediately controverted the criticism by remarking that the annual distribution costs and charges per consumer had fallen from £8·1 to £6·6 in the period under review. I would point out that during that period the total capital expenditure on generation and distribution increased by 31 per cent approximately, the generation capital by 22 per cent, and the distribution capital by 38 per cent. The installed capacity of generation increased by 32 per cent, the maximum demand by only 18 per cent, and the units by approximately 30 per cent. As regards distribution capital, the total connections increased by approximately 43 per cent and the number of consumers by 55 per cent in the same period. Thus growth was more pronounced on the distribution than on the generation side. The large supply companies which are spreading out and supplying the fringes of their areas are adding many consumers to their systems. The advantage of diversity is not so pronounced on a distribution system, as a greater degree of spare capacity is required in the mains than in the generating-station plant. Further, on the distribution side the probable rate of growth is not so certain as on the generation side. In normal industrial conditions one can estimate almost with certainty the rate of increase in generating plant for a period of some 4 or 5 years. A bigger " margin of ignorance " has to be allowed when designing the distribution system, and for this reason the effect of reductions in capital charges will be more pronounced on generation than in regard to distribution. Among the factors which have a bearing on this question are the relaxations of the Overhead Line Regulations which have attended the increase in our knowledge of the prevailing conditions, the fall in the cost of cables, and the reduction in the cost of living.

Mr. R. M. Longman: The percentage increase in distribution capital shown in Table 1 is due to the reduced generation expenses consequent upon the lower cost of the larger generating units now being installed, and the fact that there has not been a corresponding reduction in the distribution costs. A large proportion of the fall in the price of copper has only occurred within the last 4 years, and it is unfair to stress too much the figures for the period immediately after the War, when the cost of everything was abnormally high. Much of the distribution copper which has been put down in the last few years has not yet reached its full earning power. Another reason for the maintenance of the high cost of distribution is the different style of housing now favoured, with detached or semi-detached residences, wide roads, and long gardens. I feel sure that those undertakings which have spent a lot of money in the last 4 or 5 years in meeting the demand for rural and semi-rural distribution will yet get a much bigger return on their capital outlay. Table 2 raises the question of maximum demand; hitherto the maximum demands given in reports and returns of undertakings have, I am afraid, chiefly represented spot readings, or short-time peaks. When the grid scheme is in full operation the true maximum demands, over half-hour periods, will be available. The Croydon and Wimbledon figures are most interesting, and I should like to have similar curves for many towns in this area, such as Sheffield, Leeds, and Bradford. Sheffield suffered very severely in the industrial slump. The Electricity Department immediately began to tackle the domestic problem and the question of supply to the housing estates and smaller houses by assisted wiring, hire of apparatus, and prepayment meters. By these means the full effects of the industrial slump were minimized and a new and lasting load is being built up; this will give a much increased load and also an improved load factor. The way to bring about the lower distribution costs is to watch the distribution lay-out, the methods of installation and laying of service cables, and the greater use of overhead lines, and to encourage the use of more current-consuming apparatus. A brief examination of the load curves of undertakings indicates that a particular point to tackle is the night load, between 12 midnight and 7 a.m. Domestic water heating is one means whereby this huge valley can be partially filled, by arranging the heating of water during the night period. There are numerous domestic consumers in the larger areas where 2-part tariffs are in use who are getting supplies at an average figure of 0·75d. per unit or less. As an example, a household of 6 has a consumption of about 8 000 to 10 000 units per annum, and, including quite a high rateable-value charge, the average cost is 0·7d. per unit.

Mr. H. Peace: I should like to ask the authors whether any account has been taken in the paper of the cost of change-over operations. The undertaking with which I am associated has spent £40 000 in change-over work during the past 3 years, and we estimate that we have another £60 000 to spend.

Mr. W. R. T. Skinner: Fig. 13 purports to show the very considerable increase in output as the result of a change of tariff; but it occurs to me that when that change of tariff was introduced a more extensive sales campaign or, possibly, hire-purchase terms, hire terms, etc., may have been instituted. The latter would account for part of the increase, at all events. While one deplores the constancy of the efficiency of distribution capital over a period of years, it seems to me that it is explicable and to be expected. As development has gone on, an attempt has been made to supply the more sparsely populated areas and less profitable consumers. The addition of 1 000 kW of load in units of 100 kW involves more distribution capital than one block of 1 000 kW, but the effect on the station is the same in both cases. Consequently we must expect a much bigger improvement in the use of generation capital than in the use of distribution capital as time goes on. On page 108 it is stated that domestic sales will form the most important development in the near future, provided that the tariffs offered are such that the domestic services can be obtained as economically by the use of electricity as by other means. I take it that " economically " does not mean " cheaply," because there is no necessity to aim at supplying electricity as cheaply as the equivalent amount of heat can be supplied in any other form. Other factors, besides the mere amount of heat or energy supplied, come into the cost equation. Among these factors are convenience, flexibility, and adaptability, and from all these points of view electricity has the advantage.

Mr. George W. Mitchell: The annual burden due to interest and standing charges is far less on the distribution capital than on an equal amount of generation capital, and therefore the distribution department can carry capital far in excess of the generation capital while still having the same annual burden. I therefore contend that the distribution department should not, for the time being at any rate, try to keep down its costs so as to bring in a fixed number of units per £ of distribution capital. It should have some vision, and should lay mains of sufficient capacity to allow for future development. In planning a low-tension distribution system it nearly always pays to err on the high side when specifying the cross-section of the conductors. In the modern type of residential area the houses are set back a greater distance and spaced farther apart than in the older type of property, and therefore one would have expected the average price of giving a service to increase. In Hull, however, it has diminished.

Mr. J. G. Craven: It is helpful to draw an analogy between the generation and distribution of electricity and the manufacture and distribution of a proprietary article. Take, for example, a firm manufacturing a proprietary article which can be sold in every town and village in the country. They set up an efficient factory and manufacture the article by the million, concentrating in the first few years on the large towns (as with electricity). At the end of, say, 10 years the towns and thickly populated areas have become saturated by the article. The firm have by this time improved the efficiency of their factory and installed more modern plant. They wonder how they will get rid of the extra articles which they can now manufacture at a lower cost per article. Is it not a fact they will have to look to the rural areas and villages, and will not the distribution costs of the article tend to go up as a result?

(*Communicated*) This analogy might be exploited further by visualizing what would happen if the law of the country were such that the concern were compelled to manufacture and distribute the articles in 663 different areas, without authoritative control over the manufacture, or distribution by a central executive. It is not difficult to imagine the wide variations which would result in both the manufacturing and the distribution costs of the article. Is not this more or less the position of the electric supply industry to-day?

Mr. J. N. Waite: Distribution engineers are not, as a rule, responsible for the revenue earned by the distribution networks. That responsibility rests with the management, and, so far as the paper is a criticism, it is a criticism of management. If there is one fact which ought to be recognized by all those connected with electricity supply it is that the real way to cheapen supply is to increase sales, because over 80 per cent of the total costs are standing charges. Throughout the paper and their replies to discussions at other Local Centres the authors have stressed the importance of the cooking load. Many engineers regard water heating as more important than cooking, but they must be ignoring certain facts. An overwhelming proportion of houses are inhabited by working-class people, or people of very modest means. In Hull, 85 per cent of the total houses are rated at £15 or under. The inhabitants of such houses cannot afford luxuries, but they have all got to cook, and with a proper tariff and hire facilities for cookers it is possible for them to use electric cooking at a cost not greater than that of their existing methods. It is therefore possible to get electric cooking adopted on an economic basis for all houses. The same cannot be said for water heating, for so far as the working class are concerned a constant and copious supply of hot water would cost more than they normally spend on this convenience, and therefore would not be adopted to the same extent as electric cooking. Whilst water heating is a valuable load, the market is not so large as that for cookers. The installation of an electric cooker and wash-boiler will increase the consumption of a working-class house by about 8 times, as compared with lighting only. The increase in distribution capital necessary to give a full supply, as compared with a supply for lighting only, is from 30 to 40 per cent. Owing to the very high diversity the peak load at the time of an undertaking's winter peak is very little higher than when lighting only is installed. As the local distribution peak load occurs in the morning in the summer time, at a period when most undertakings welcome an extra load, it becomes an economic possibility to give domestic supply at a relatively low rate. [Mr. Waite here exhibited a slide giving an analysis of the costs of supplying a working-class estate of 500 houses (see vol. 72, p. 358).] Some 4½ years ago Hull started a large development programme, and in the last 4 years it has incurred a capital expenditure of over 1½ millions sterling, of which over 1 million was expended on distribution. Despite this relatively huge capital expenditure, owing to the increased output obtained by lowering prices the actual total cost per unit has decreased each year, and has now reached the lowest figure obtained in the history of the undertaking; in addition, an average net profit of £51 000 per annum has been made. (Mr. Waite here exhibited a number of slides showing results obtained over the 4 years.) When analysing results it is important to bear in mind that in the business of electricity supply it is inevitable that income should lag behind capital expenditure. As time goes on, load is built up and the income increases with relatively small additional capital expenditure, so that capital charges go through a cycle of sudden increase followed by a progressive decrease. This characteristic is shown by the figures given in Table F, which refers to the Hull undertaking. This cycle of sudden increase and progressive decrease of capital charges is very definite as regards generation capital, but is often masked in regard to distribution capital by the fact that usually a number of cycles at different stages are in operation at the same time, and thus tend to average out. Nevertheless, the cycles are there, and therefore to obtain a true perspective of the financial results of development it is necessary to give credit for an increased income in future years which will accrue as the load on the distribution system is developed. The figures in Table F show this characteristic and also that the undertaking is progressively reaping the benefit of the relatively large distribution expenditure in previous years. It may be expected that the capital charges per consumer and per unit will progressively decrease. It has been said that supply undertakings live on diversity; in my opinion the diversities which actually exist in all

TABLE F.

Year ended 31st March	Distribution capital expenditure during year	New consumers connected during year	Average distribution capital per new consumer
	£		£
1931	346 620	8 211	42
1932	319 833	8 974	35
1933	219 034	9 082	24
Six months ended September 1933			
	51 723	3 673	14

classes of supply are much greater than is generally believed. The lower the load factor the greater the chance of diversity, and diversity can result in a good load factor from a group of consumers whose individual load factors are very low. For example, in the working-class housing estate of 500 houses in Hull it was found that the load factor of the individual houses ranged round 3 per cent, but the load factor of the estate as a whole, based on the maximum demand at the time of the peak of the undertaking, was 65 per cent. Thus, despite the low load factor of the individual consumers, the diversity created a very good load factor for the group. Domestic electrification gives a higher diversity than any other class of supply, and therefore fully warrants a relatively low charge, despite the low load factors of the individual consumers. The authors are fully justified in their view that the way to real improvement is increase of sales, and in their stressing of the importance of the domestic market. It is fairly obvious that many engineers do not realize the importance of the effect of diversity on selling price, for many contend that they cannot sell at a lower average price than they pay for their supply. Assume they are buying on the Mid-East England tariff of £3 10s. per kW plus 0·186d. per unit. With a load factor of 30 per cent the average price would be 0·51d. per unit. The idea that a bulk-supply undertaking's tariffs must be bulk-supply terms plus distribution standing charges and losses, ignores diversity. Very few consumers make their actual maximum demand at the time of the undertaking's maximum demand, and therefore, in effect, the undertaking can sell many more kW of maximum demand than it purchases; so that the standing part of its tariffs may be much lower than the full average standing charge of the undertaking. There is an enormous future for domestic electrification, and in view of the high diversity associated with this class of supply all undertakings can afford to offer an attractive tariff with a follow-on rate not exceeding $\frac{3}{4}$d. per unit; and, in many cases, not exceeding $\frac{1}{2}$d. per unit. A low follow-on rate is essential to develop the load, and there is no economic reason why the load should not be developed. In conclusion, I would pay a tribute to the authors for their courage in criticizing the results of electricity supply undertakings as a whole. Their main contention—that many undertakings are backward in their development of supply—is undoubtedly true; and unless the industry as at present organized does provide a cheap and abundant supply in a large majority of cases, then we cannot complain if some other form of organization is brought into being.

Mr. J. M. Kennedy and **Miss D. M. Noakes** (*in reply*): Mr. Mills's diagram (Fig. L) indicates very clearly the need for increasing sales of electricity in order to reduce the cost per unit. It no doubt relates to total cost including generation, and the pence per unit for electricity sales is, as one would expect, approximately double the figure given in Table 6. We are glad to have his support for the general conclusions to be drawn from the paper.

Mr. Dundas criticizes our suggested comparison of generation and distribution efficiencies. In this connection we would refer him to our earliest reply,* where we produced an analysis of the reduction in generating costs which ought to apply equally to distribution. He also criticizes the examples we give of progressive undertakings, on the ground that they are of a highly residential nature; we suggest in reply that there is no reason why industrial districts should not develop the domestic load as well as districts which may be considered to be purely residential. We would also refer him to the curve given in Fig. M, in reply to Mr. Longman's remarks. We agree with Mr. Dundas that in order to meet future developments, capital is needed in advance of immediate requirements, but if the spending of capital is followed up by sufficiently active propaganda and if sales are encouraged at the same time in districts where mains have already been laid, there is no reason why the units per £ of capital should fall or distribution costs increase. Attention may be drawn to Mr. Waite's remarks on this subject. Mr. Dundas considers that a 50 per cent load factor is exceptionally high, even on a daily basis, but Mr. Waite's experience in Hull on a working-class estate indicates that it is by no means an unattainable ideal, and in the area of the Electricity Board of Northern Ireland daily load factors of well over 60 per cent have been commonly recorded.

We are glad that Mr. Thwaites supports our conclusions and we agree that the problem of the size of area is one which needs most careful consideration. We do not agree, however, that engineers are not concerned with the question of administration; because in the electric supply industry administrative, financial, and technical, problems are inevitably and closely interlinked.

We suggest to Mr. Evans that he is unduly pessimistic in his estimates of future sales. If he will plot the total sales recorded year by year and note the improvement in 1932–33, 1933–34, and already recorded in the first 4 months of 1934, he will see that there is every reason to expect that the Weir Committee's estimates of sales in 1940 may be realized. Surely, however, it is just as rash for Mr. Evans to forecast in 1934 the sales in 1951 as it was for the Weir Committee in 1924 to forecast the sales in 1940. We do not agree with the remarks of Mr. Evans about Fig. 6. In fact, the diagram clearly shows that the sales of electricity are not governed solely by the average price; if this were so, all the points would lie on the curve. The position of any particular undertaking to one or other side of the curve depends largely upon its degree of saturation and to a certain extent upon the nature of the undertaking, but any undertaking should, if progressively developed, follow over a series of years a curve which is similar in shape to that given in Fig. 6. We quite agree with the figures which Mr. Evans quotes as to the percentage increases in generation and distribution capital, but he does not attempt to explain the reason why the distribution capital has increased more than the sales of units. Mr. Evans reiterates what we pointed out in the paper, that in spite of the reduction in capital cost and charges per consumer, the average number of units sold per £ of distribution capital has decreased. This simply proves the case which we tried to make in the paper, that the sales policy throughout the country has not been active enough to bring about a more efficient use of the distribution capital.

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* See vol. 73, p. 156.

We quite agree with Mr. Longman that the capital spent on rural and semi-rural distribution schemes has not yet reached its full earning power, but, as the development in these areas should have been accompanied by an increased activity of power and domestic sales in areas of a more urban character, there should not have been any reduction in the average units sold per £ of capital if a sufficiently attractive policy had been followed. Mr. Longman asks how the curves for Croydon, Wimbledon, and Wallasey, would compare with similar curves for industrial towns in the Mid-East England area; we therefore include a diagram (Fig. M), showing similar curves for Leeds, Bradford, Huddersfield, and Sheffield, and giving the Croydon curve for comparative purposes. It will be noted that, as regards total development over the period under review, Huddersfield is as good as any of the others.

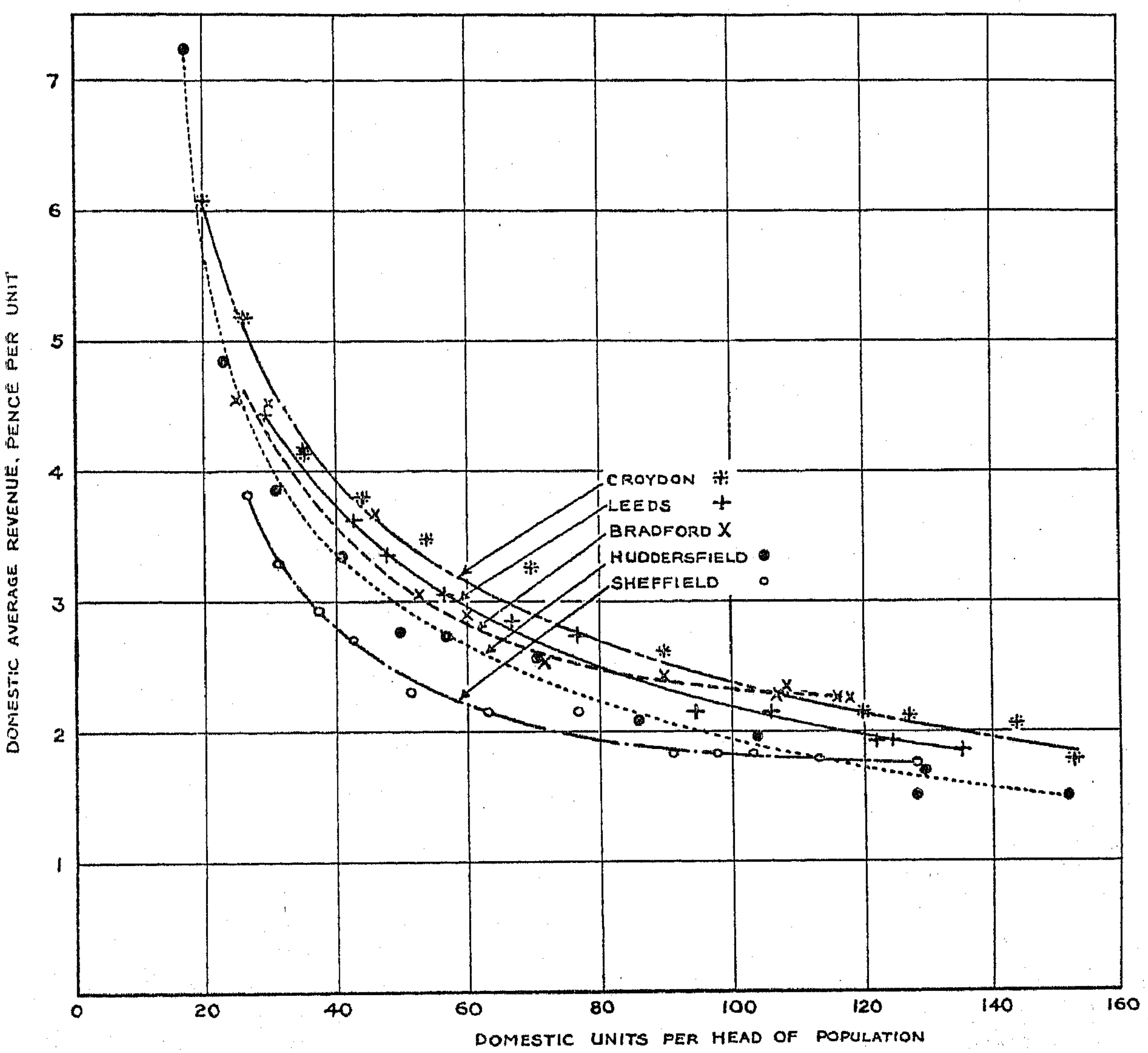

FIG. M.

Mr. Peace raises the question whether the cost of change-over operation will have weighted unduly the distribution capital or annual cost. Undoubtedly, in some cases the change-over from direct current to alternating current and the re-laying of obsolete mains has been charged to revenue and will have thereby increased the annual distribution costs, but we do not think that the amount so included would affect our general arguments in any way.

Mr. Skinner suggests that the results shown in Fig. 13 were due not only to the introduction of a 2-part tariff but also to an extensive sales campaign, including hire of apparatus. We have no doubt that this was so, and in the paper we pointed out that all these factors are essential to the success of electrical development. Mr. Skinner also mentions that recent development has taken place in the more sparsely populated areas and in connection with less profitable consumers. We dealt with this point fully in our earlier reply,* where we drew attention to the fact that the capital and annual distribution costs per consumer have fallen during the last 4 years, and also referred to the striking results obtained in working-class property by Mr. Robinson of Liverpool, Mr. Waite of Hull, and others. We agree with Mr. Skinner that convenience, flexibility, and adaptability, are all factors in favour of domestic electrification, but we certainly do not agree with him when he says " there is no necessity to aim at supplying electricity as cheaply as the equivalent amount of heat can be supplied in any other form." If we are to obtain the working-class domestic load which is so important we must offer electric supplies, including hire of apparatus and the provision of all wiring, etc., at an inclusive figure which is certainly no more, and preferably somewhat less, than the cost to the consumer of any other form of service; the results already achieved by several undertakings prove that it is possible to do this and that the load so obtained is an economical proposition.

We would point out to Mr. Mitchell that the planning of a distribution undertaking should be such that, over a series of years, the units per £ of distribution capital would increase with increased capital expenditure. We quite agree that adequate capital expenditure is necessary to ensure progressive development, but it must be accompanied by a sufficiently active selling policy throughout the whole of the undertaking to ensure increased sales of units, so that the capital year by year on the average will be used more efficiently. As Mr. Mitchell remarks, one might expect the average price of giving a service in modern residential areas to have increased, but, owing to the cheaper type of transmission and distribution which is possible, it is found that the capital cost per consumer is decreasing. This may also be accounted for in some cases by the unduly high levy on the consumer for the cost of the service cable.

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* *Loc. cit.*

We do not think that Mr. Craven's analogy is quite fair, because the supply of electricity in urban areas is so far from saturation and the distribution in rural areas represents such a very small proportion of the whole. We are quite in agreement, however, with his conclusion that some form of control over the 663 separate undertakers is essential if there is to be a rational development in the sales of electricity and the tariffs adopted.

We thank Mr. Waite for his wholehearted support of our contentions and for the most valuable evidence he gives for the refutation of the various criticisms of the paper to the effect that increasing electrical development is bound to result in fewer units being sold per £ of distribution capital. We welcome Mr. Waite's support for the necessity of developing the cooking load, and we are quite convinced from what we have heard all over the country that this is the most important development which can take place in the domestic side of the electricity supply business during the next few years. It is essential, however, that the total cost to the consumer, including service, wiring, hire and maintenance of cookers, and the whole cost of electricity, should be no greater than the amount the consumer is paying for gas or other means at present used for cooking. Mr. Waite points out that the diversity factor of this class of load is so great that there are few, if any, progressive undertakings of reasonable size which cannot afford to offer sufficiently attractive tariffs.

Knowing that "an ounce of fact is worth a ton of theory," we hope that our critics will study carefully the remarks of Mr. Waite and others who have been successful in developing this class of load, and will appreciate that some steps are necessary to ensure that all undertakings are developed on progressive lines.

INSTITUTION NOTES.

Overseas Members and the Institution.

During the period 1st May to 30th June, 1934, the following members from overseas called at the Institution and signed the "Attendance Register of Overseas Members":—

Ashley, W. H. (Poona, India).
Banks, E. B. (Calcutta).
Carson, A. H. (Johore, F.M.S.)
Clarkson, T. R. (Auckland, N.Z.).
Clayton, J. R. (Assam).
Cullwick, E. G., M.A. (Vancouver, B.C.).
Crawshaw, E. (Calcutta).
Eastgate, C. C. T. (Calcutta).
Goodman, C. W., B.E. (Sydney).
Graham, H. (Shanghai).
Hanlon, E. M. G. (Hong Kong).
Henderson, D. H. P. (Calcutta).
Hughes, H. M., B.Sc.(Eng.) (Calcutta).
Meadmore, C. C. C. (Simla).
Milne, F. L. (Lahore).
Nagel, W. L. St. M. (Colombo).
Nordwald, D. (Natal).
Percival, A. J. (Shanghai).
Reay, G. H. N. (Singapore).
Rogers, T. (Penang).
Row, D. P. (Karachi).
Shilson, L. J. (Cairo).
Thomas, Ernest (Nassau, Bahamas).
Whittaker, H., B.Sc.(Eng.) (Moghalpura, India).
Whittick, R. B. (Buenos Aires).
Wilson, J. H. (Shanghai).
Young, A. H. (Jamaica).

Nominations for Election to the Council.

In addition to those members nominated by the Council (see vol. 74, page 602) the following Associate Member has been nominated for ballot as an Ordinary Member of Council:—

J. W. THOMAS, LL.B., B.Sc.

(Nominated by A. S. Barnard, J. Frith, M.Sc., T. E. Herbert, O. Howarth, A. L. Lunn, E. C. McKinnon, T. A. G. Margary, J. H. Parker, G. F. Sills, and J. N. Waite.)

Premiums.

In addition to the Premiums mentioned on page 602 (vol. 74) of the June issue of the *Journal*, the Council have awarded the following Premiums for papers read before the Students' Sections during the session 1933–34:—

Premiums of the value of £10 *each:*

Author	*Title of Paper*	*Section where read*
T. D. OSWALD, B.Sc.	"Tapping the High-Tension Grid"	North-Eastern
R. P. E. TABB	"The Induction Voltage Regulator"	South Midland

Premiums of the value of £5 each:

JAMES R. ANDERSON	Chairman's Address	South Midland
T. H. BRIDGEWATER	" Some Aspects of Television Reception "	London
S. FARRER	Chairman's Address	North-Western*
J. H. S. GILLINGHAM	" The Selection and Lay-out of Electric Arc Welding Plant "	London
J. E. L. ROBINSON, B.Sc.(Eng.)	" Over - Voltages and their Influence on Transmission System Design "	North-Western
F. JERVIS SMITH	Chairman's Address	London
D. R. TURNER, B.Eng.	" Carrier-Current Telephony "	South Midland
K. J. R. WILKINSON	" Alternating-Current Bridge Circuits "	South Midland
EMRYS WILLIAMS	" Sound "	Mersey and North Wales (Liverpool)
R. O. YARDLEY	" Some Developments in Railway Signalling "	North Midland

World Power Conference.

The *Transactions* of the Scandinavian Sectional Meeting of the World Power Conference held at Stockholm in June and July, 1933, have now been published. They include all the papers and discussions of the Meeting, and comprise seven volumes containing about 4 000 pages. The contents of the volumes are as follows: Vol. 1, General; Vol. 2, Electric Power; Vol. 3, Solid and Liquid Fuels and Gas; Vol. 4, Power and Heat Combinations: Industries requiring Steam for Heating Purposes; Vol. 5, Iron and Steel Industry, Electrical Heating, Transmission and Adaptation of the Motive Power to Industrial Machinery; Vol. 6, Railways, City and Suburban Traffic; Vol. 7, Marine Transport.

The price of the set of seven volumes is £8 15s., but the individual volumes can be purchased separately, if desired. Orders for copies should be sent to Messrs. Percy Lund, Humphries, and Co., Ltd., 12 Bedford Square, London, W.C.1, from whom full particulars and a detailed prospectus can be obtained.

Current Loading of British Standard Paper-Insulated Cables: Effect of Thickness of Insulation (E.R.A. Report, Ref. F/T80).

In 1924 the British Electrical and Allied Industries Research Association issued Ref. F/T14: " Tables of Permissible Current Loading of British Standard Impregnated Paper-Insulated Electric Cables (B.S.S. No. 7—1922) with Explanatory Notes," in which are given current ratings of cables based on the dimensions specified in B.S.S. No. 7: " Insulated Annealed Copper Conductors for Electric Power and Light including Voltage Tests."

B.S.S. No. 7 has been superseded by B.S.S. No. 480: " Dimensions of Metal-Sheathed Paper-Insulated Plain Annealed Copper Conductors for Electricity Supply, including Voltage Tests." Revision of Ref. F/T14 to take account of changes in rating arising out of changes in dimensions, new sizes and types of cable is under consideration. Pending the completion of this work it may be assumed that any changes in rating arising out of the present changes in dimensions only will be very small, amounting to 5 per cent only in rare cases.

The temperature-rise of the core depends on two terms which are affected in opposite directions by a change in insulation thickness. An increase in wall thickness causes an increase of thermal resistance of the insulating material, thus tending to raise the temperature but, at the same time, decreases the difficulty in disposing of the heat produced, as the external surface is also increased. Subject, therefore, to the qualifications described in Ref. F/T14 respecting the thermal resistivity of the dielectric and the soil, temperature limits, depth of laying, etc., it may be assumed that the current ratings for the cables covered by B.S.S. No. 480 are practically the same as for corresponding sizes and types in Ref. F/T14. The current ratings for 460-, 1 000-, and 1 500-volt cables may be assumed similar to those for 660-volt cables of the same type and construction in Ref. F/T14.

Elections and Transfers of Members.

At the Annual General Meeting held on the 10th May, 1934, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Acworth, Donald George W., M.A.
Donkin, Bryan.
Donovan, Walter, Junr., B.Sc.
Flurscheim, Cedric Harald, B.A.
Hodgson, Kenneth George, B.A.
Lupton, Hugh Ralph, M.C., M.A.
Mellor, Ramsden.
Miles, William George H., Lt.-Col. R.M.
Miller, Reginald Charles.
Mirk, David Blair, B.Sc.
Polydoroff, Wladimir John.
Rowse, Arthur Albert, M.A., B.Sc.

Companion.

Guest, The Hon. Oscar Montague, Major.

Associates.

Adam, Duncan.
Attrill, Harry James.
Beeby, Walter Lawrence.
Booth, Christopher Hodgson, Electrical Lieut., R.N.
Cant, John Garton.
Claughton, Alfred.
Clements, Bert Mark.
Ganguly, Shiba Prosad.
Kenworthy, Harold Charles.
Lee, Edgar Morton, B.Sc.
McInally, William.
Roy, William Conrad.
Smith, Leonard Stanley.
Taylor, Ernest.
Wilcox, Edward James.

Graduates.

Abrahamson, Arnold Mogens, B.Sc.
Allen, Roy.
Fairfield, Ronald McLeod.
Forrest, Ronald William.
Low, James Paton, B.Sc.
McLeod, Godfrey Hilton.
Millen, Thomas Stanley, B.Sc.
Patrick, Percy Ellis.
Rutherford, John Gladstone, B.Sc.
Scott, Henry William.
Tait, John Ernest, B.Sc.
Tweedale, Ronald.
Westaway, George Andrew.
Yorke, Ian, B.A.

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* Also delivered before the Mersey and North Wales (Liverpool) Students' Section.

Students.

Adams, Cyril.
Akhurst, Fred Kingsnorth.
Alger, Sidney James.
Allum, Elliott St. Anthony.
Anderson, Ronald George.
Athavale, Sadashiva Laxman R.
Banks, Albert Robert J.
Barclay, Ernest George S.
Beck, Arnold Hugh W.
Bittles, Samuel George.
Bond, Ian Beaumont.
Brooker, Ronald James.
Brown, Thomas Hylton.
Bruce, James Graeme B.
Burke, Clifford Leonard L.
Campbell, Wilson William.
Chakravarti, Sitanshu-Shekhar.
Chambers, Alfred George.
Chapman, John Henry.
Chona, Baij Nath.
Clarke, Walter Parkinson.
Clunas, Ian Stuart L.
Cowan, James MacMillan.
Cross, Donald Leslie.
Cross, Hector Derek.
Das, Indra Narayan.
Davey, John Newton.
Dewar, Duncan Alexander.
Doraiswamy, K. S.
Eustace, Ernest Ralph.
Falk, Alan David.
Felgate, Leonard John W.
Flack, Phillip Douglas.
Fry, Maurice Frederick.
Gale-Wise, Claude Beering.
Garfitt, Dorothy Ellen M. (Miss).
Goodchild, Reginald Victor.
Graver, Leonard James.
Grobler, Johannes Martinus.
Hafiz, Ahmad Adnan.
Harris, Alfred William.
Hawkins, Cyril George.
Headland, Robert Charles C.
Hewett, Basil Scrymgeour.
Higgins, William Godfrey G.
Hoar, James William.
Hogg, Ian Henry.
Houston, David.
Iyengar, H. S. Krishna.
Jefferies, Edward Parks.
Jeremiah, C. John.
Johnson, Eric Samuel.
Kavade, Ganpatrao Lakshamanrao.
Kerim, Abdul.
Kilpin, John Cecil.
Koll, Otto Archibald.
Leong, Sik Aun, B.Sc.
Lockhart, Andrew Jones.
Machell, Thomas.
Mack, Henry Allen.
Marslen-Wilson, David William.
Marwaha, Ram Saran D., B.Sc.(Eng.).
Mehta, Kirtikumar Hirabhai.
Minett, Graham Rowson.
Morris, Kenneth Stapleton.
Mukerjee, Birendra Nath.
Narula, Daljit Singh.
Nicol, James Campbell B.
Padmanabhan, K.
Palmer, Thomas Andrew.
Parthasarathy, Morappakkam Josyam.
Patail, Sulaiman Mohammed.
Patrick, Roy Edwin.
Prior, Dennis Hugh.
Pugh, Charles Trevor.
Quartley, Arthur John L.
Rawlings, John Herbert.
Reed, James Ramsay.
Robertson, William Shepherd.
Ross, Alexander Duncan.
Roy, Provanshu Kumar, B.Sc.
Sander, Glen Certhew H.

Students—continued.

Sassoon, Reuben.
Seethapathy, A. P.
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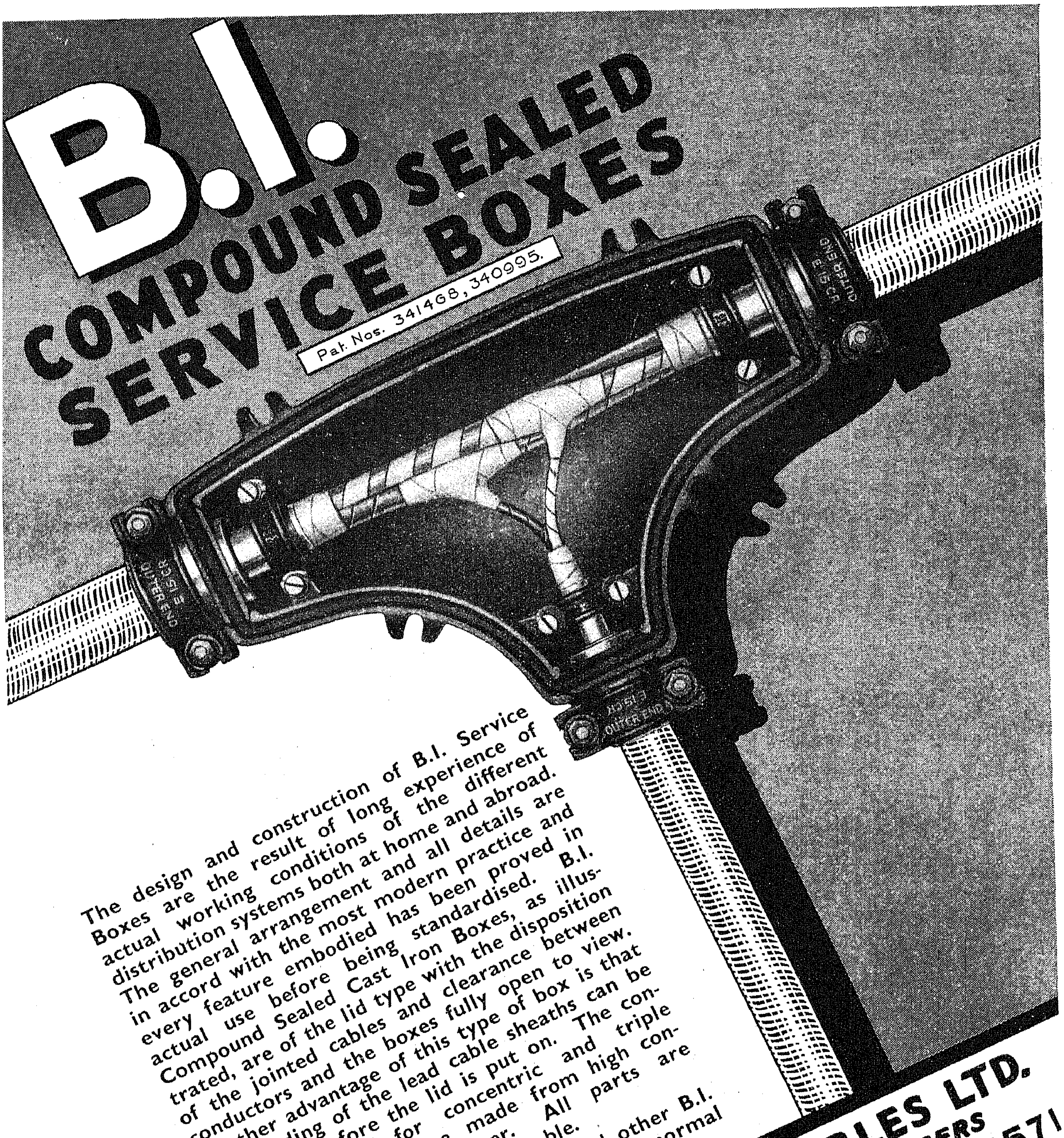

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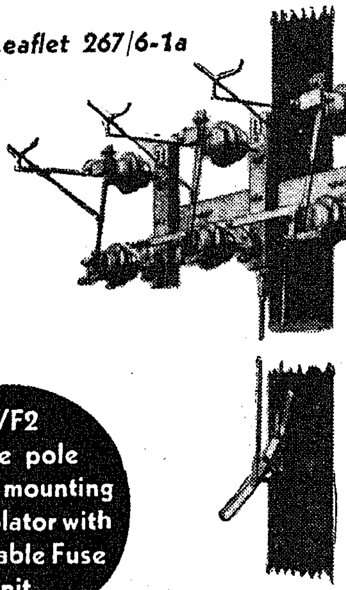
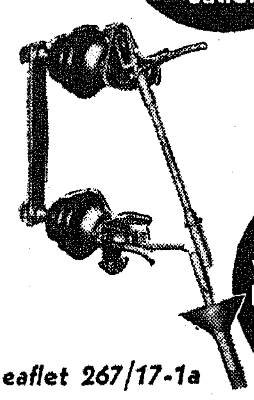


RGD1 Vertical mounting switch for single and H-Pole applications

Leaflet 267/6-1a



WF2 Single pole vertical mounting Fuse Isolator with detachable Fuse Unit

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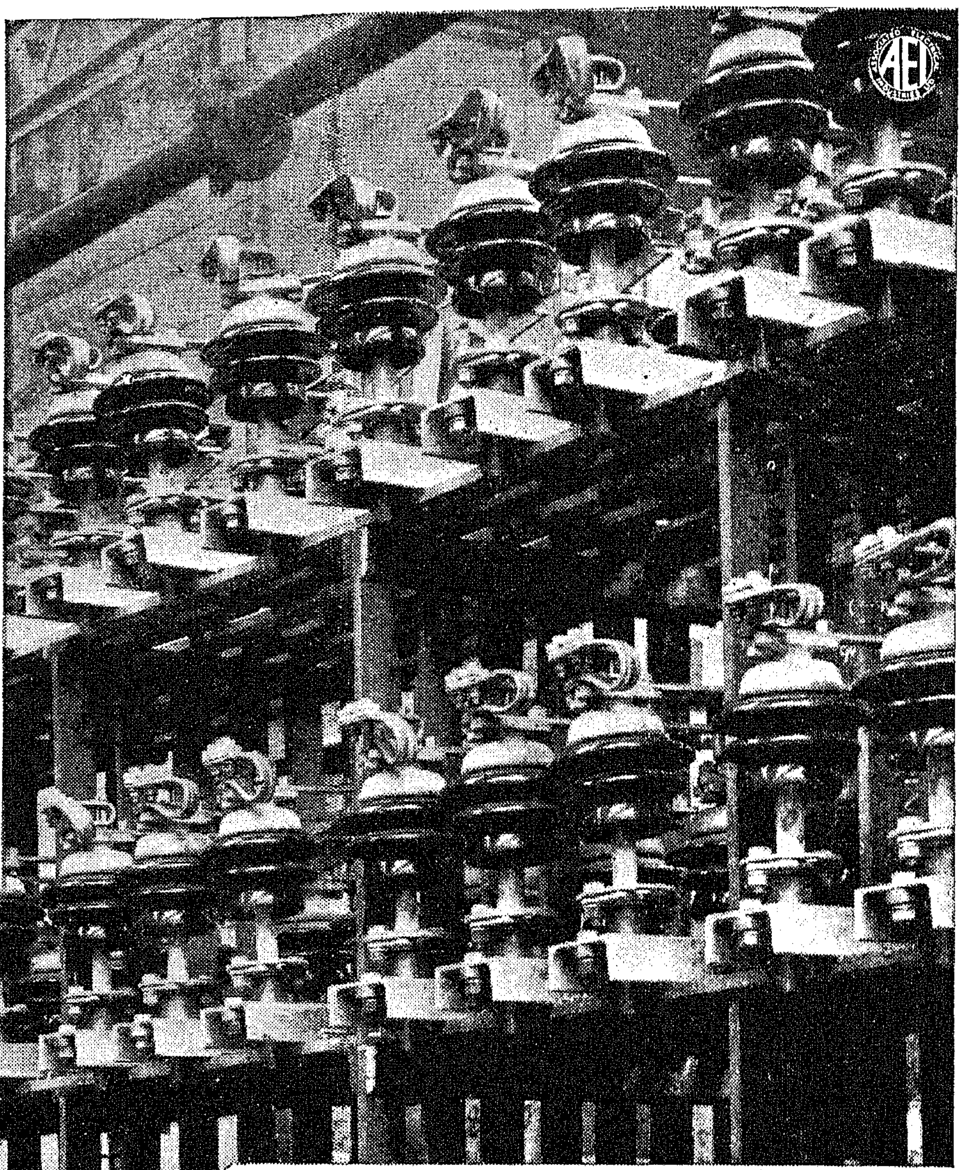

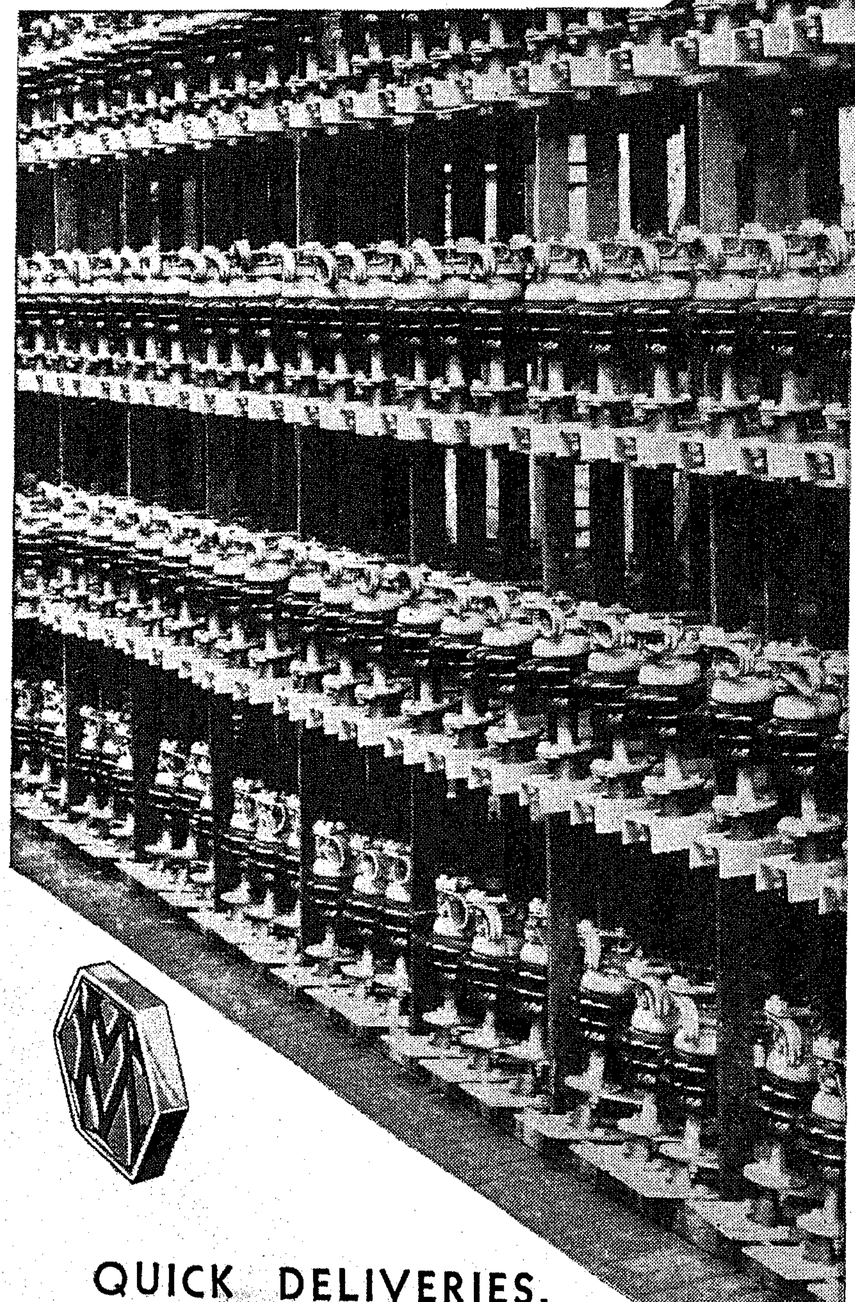

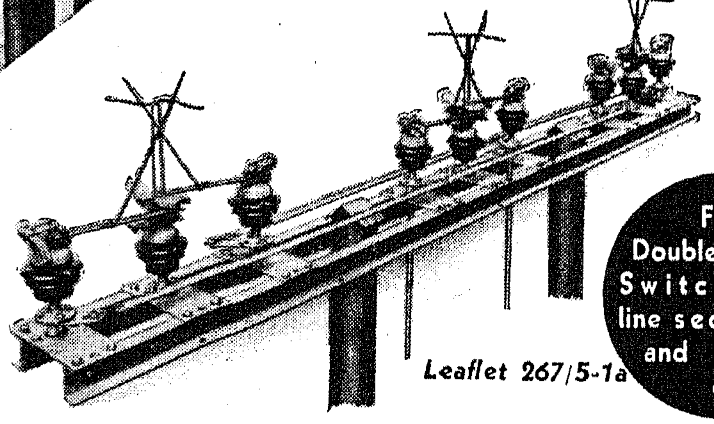

FLR Double Selector Switch or for line sectioning and tapping off

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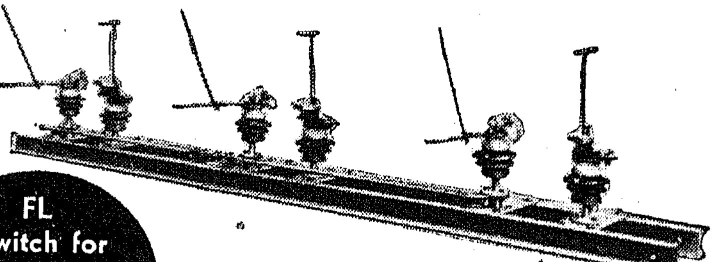
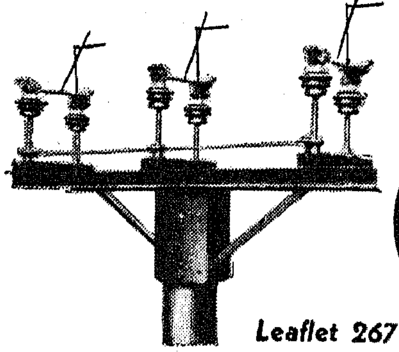


FL Switch for sectioning, teeing-off or terminal switch

Leaflet 267/5-1



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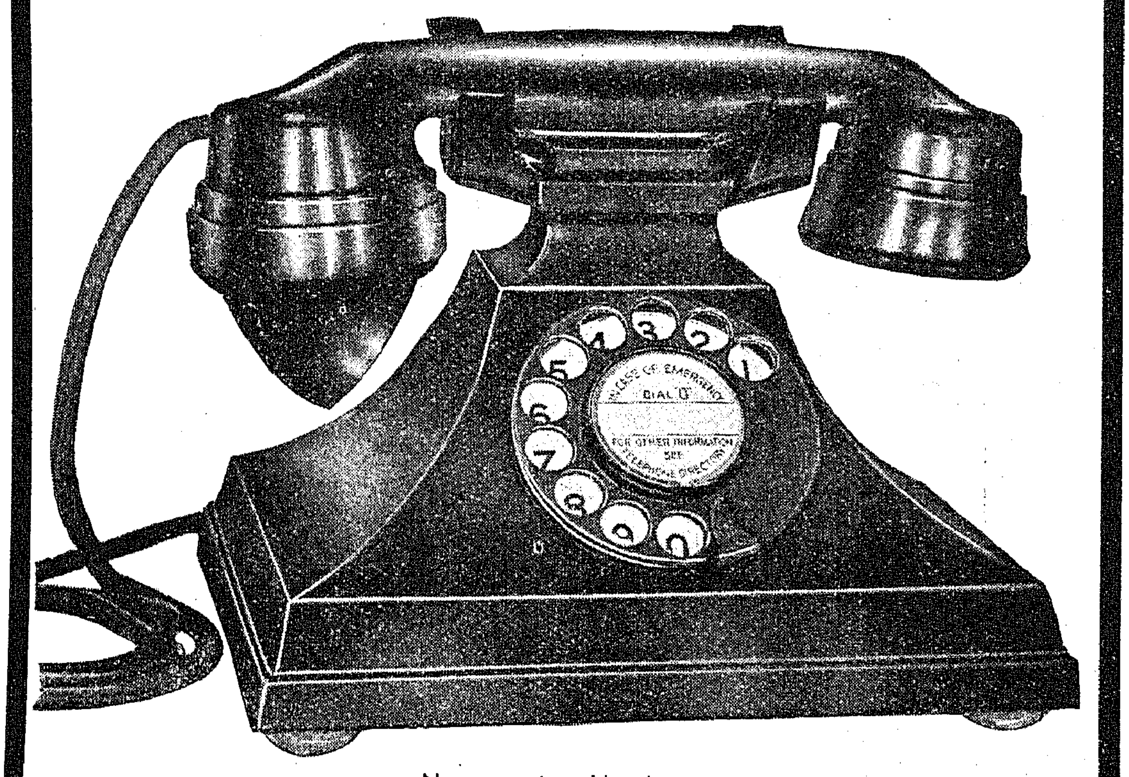

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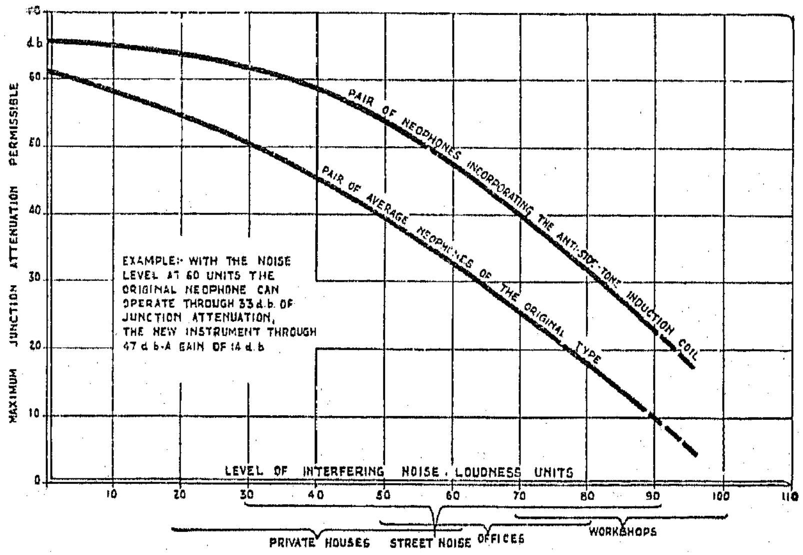

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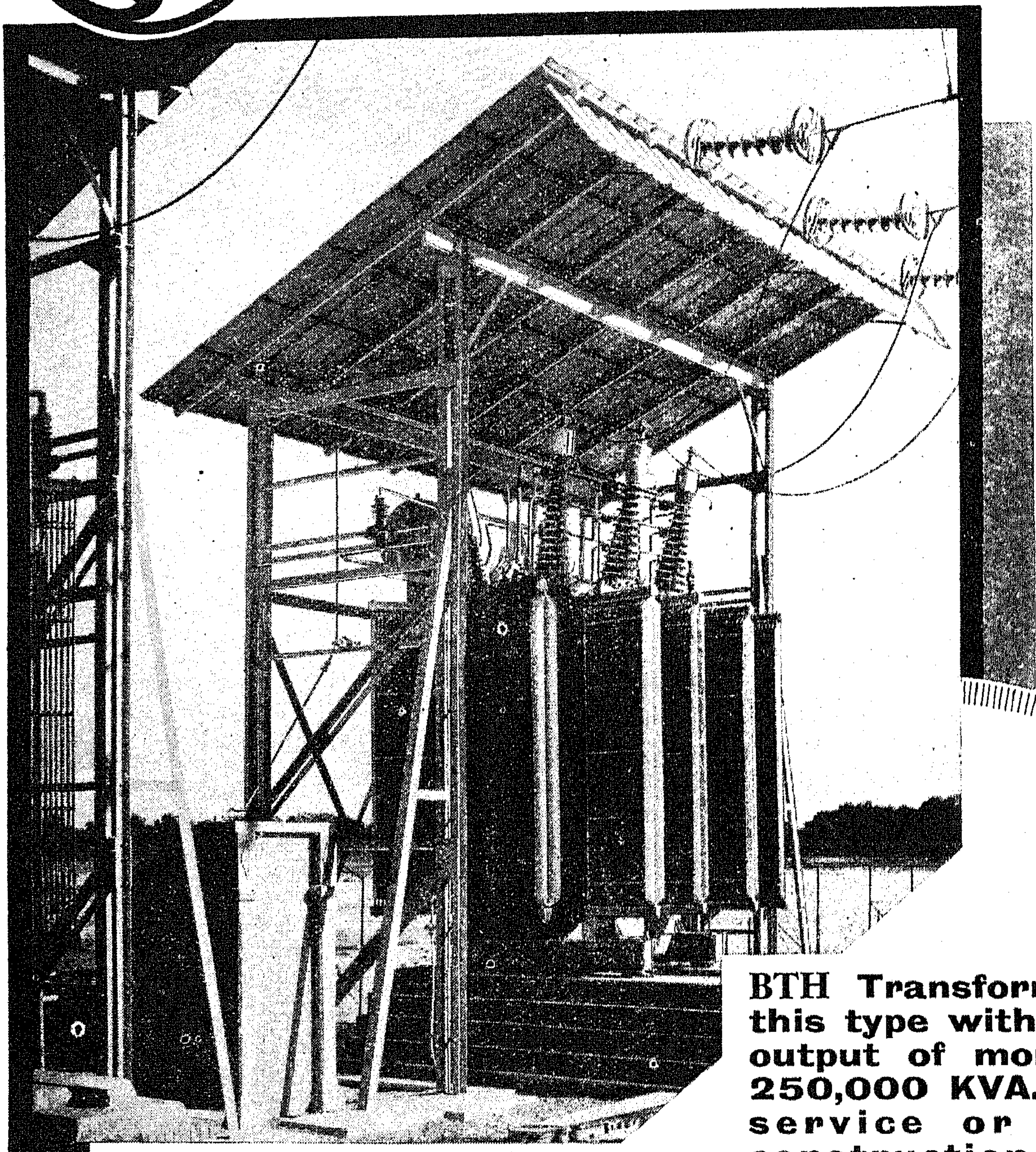

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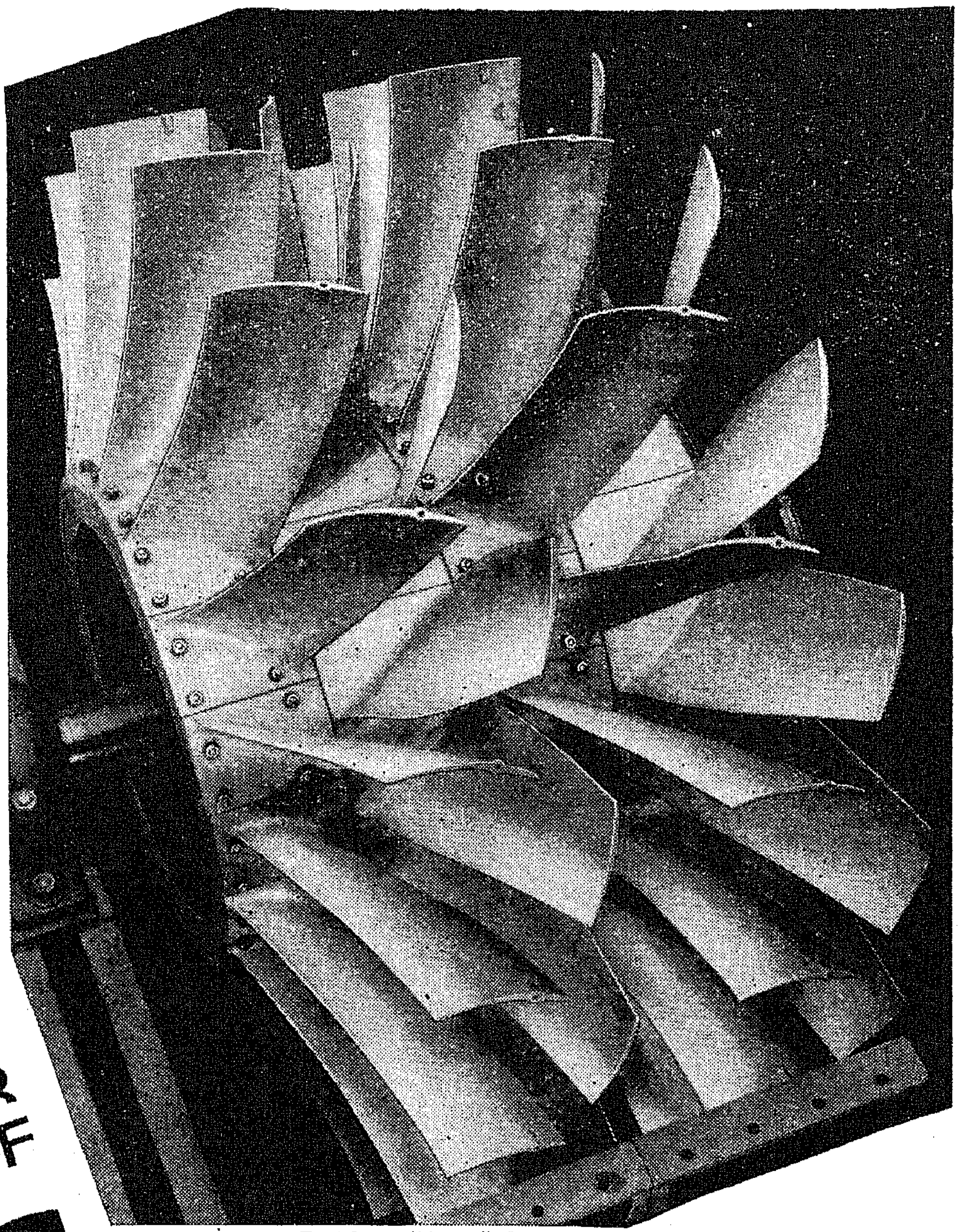

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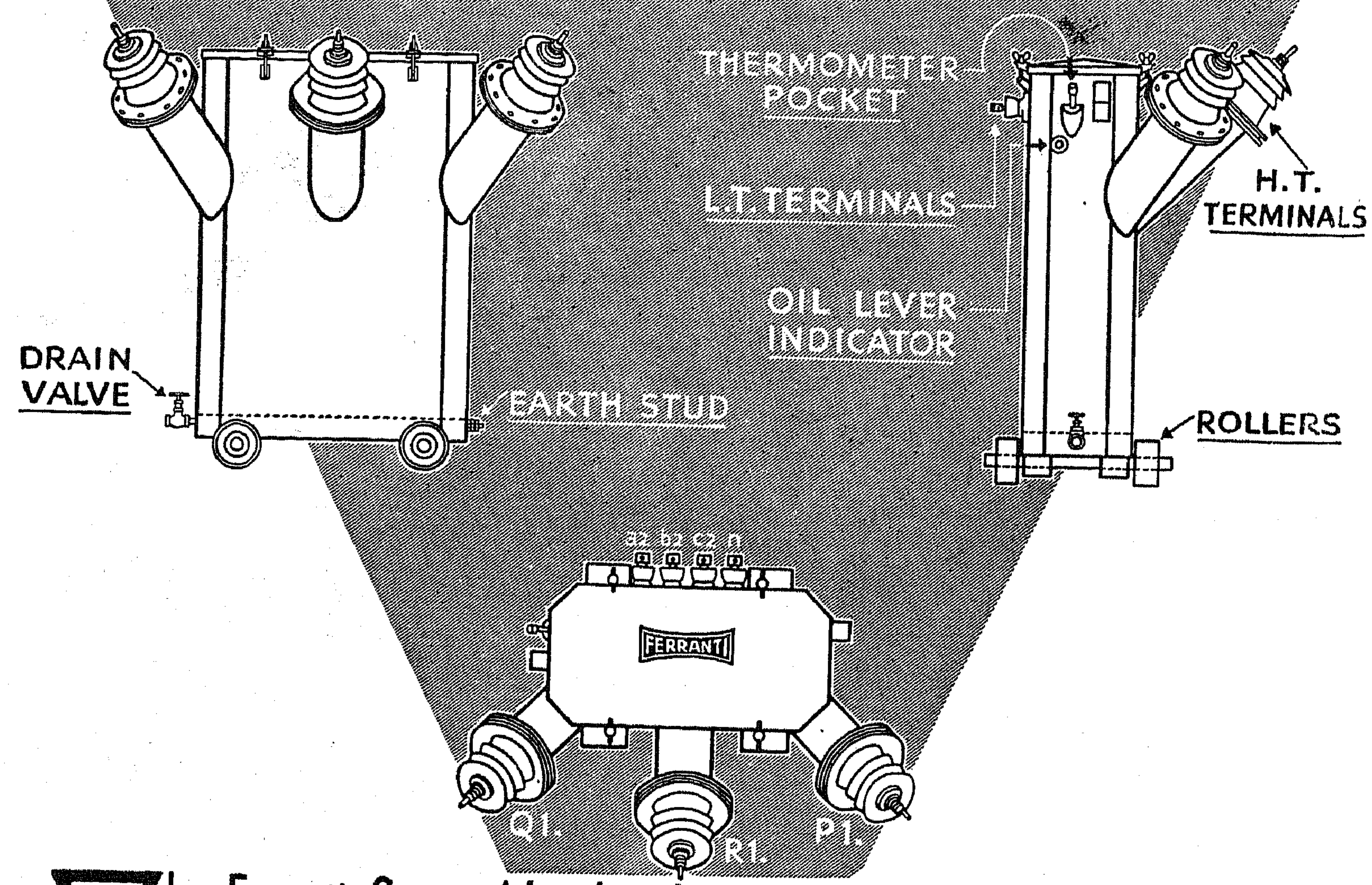

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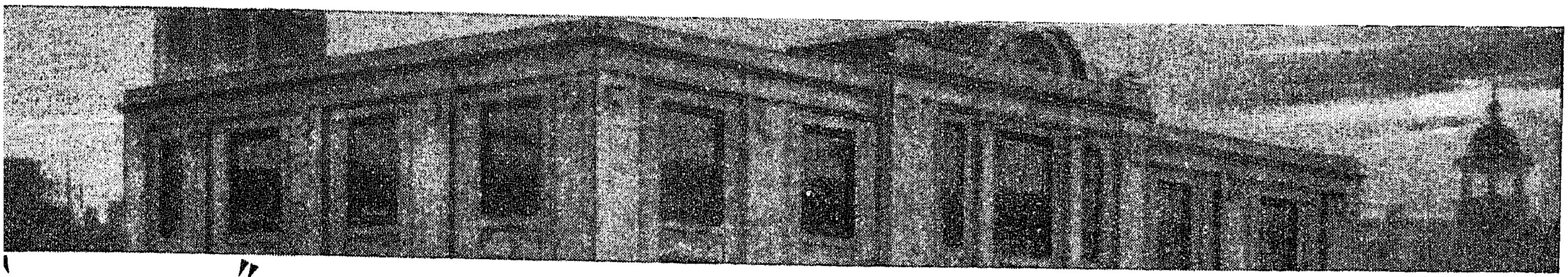

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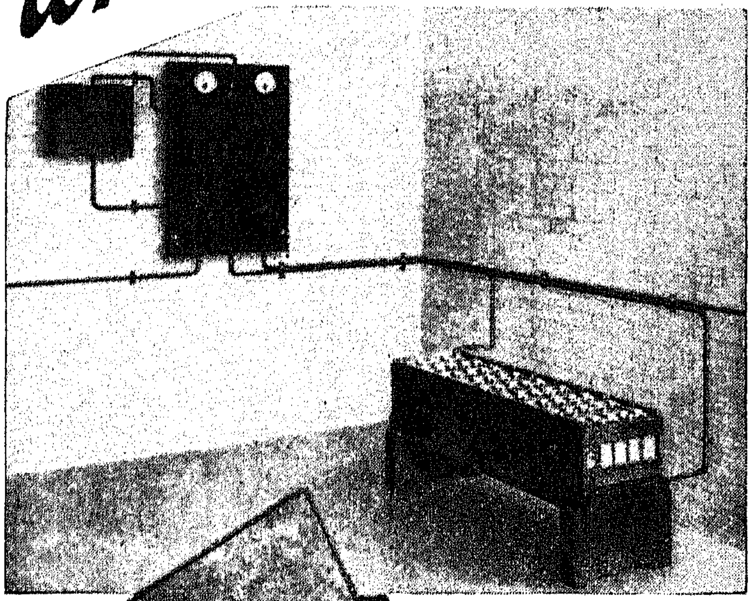

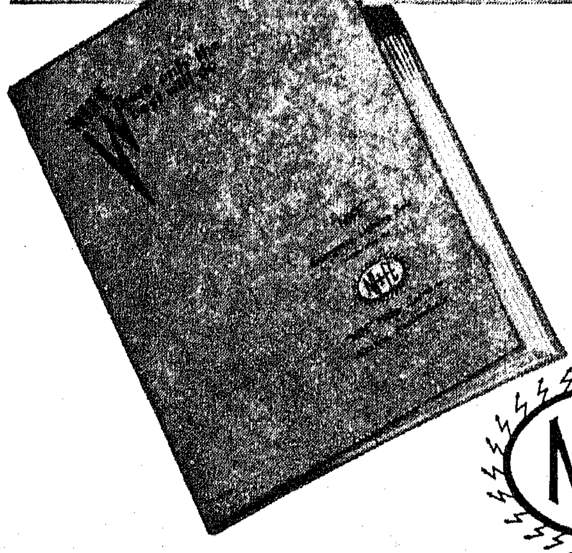

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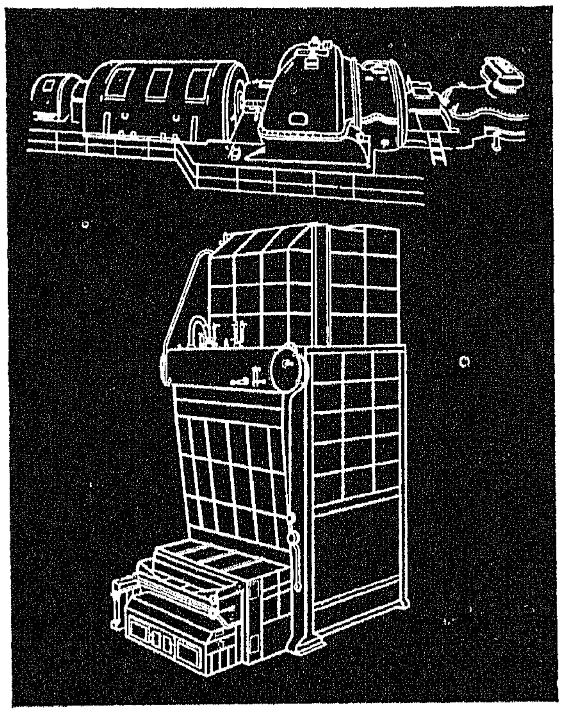

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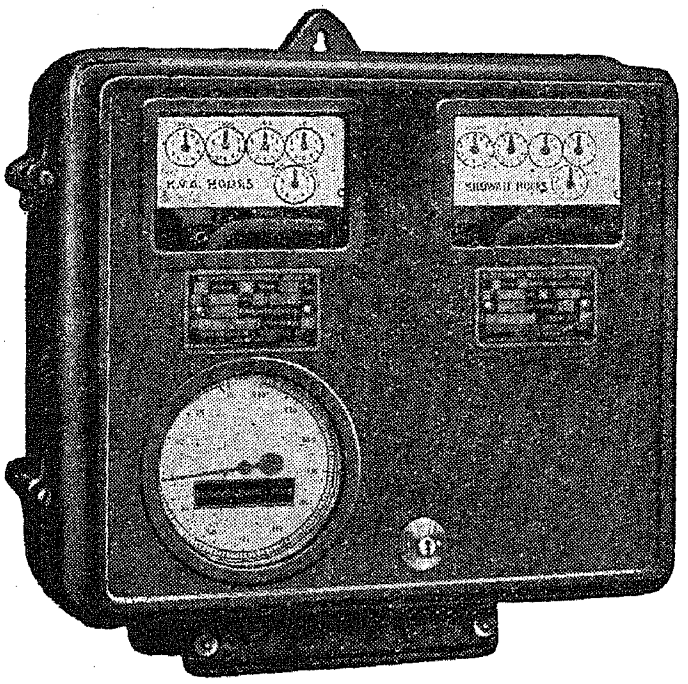

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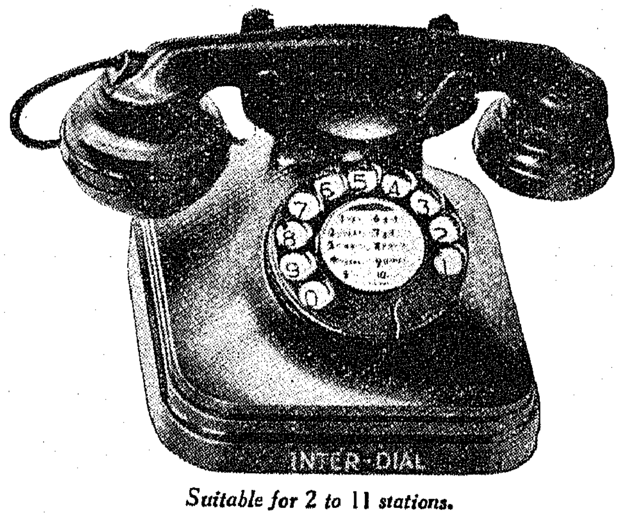

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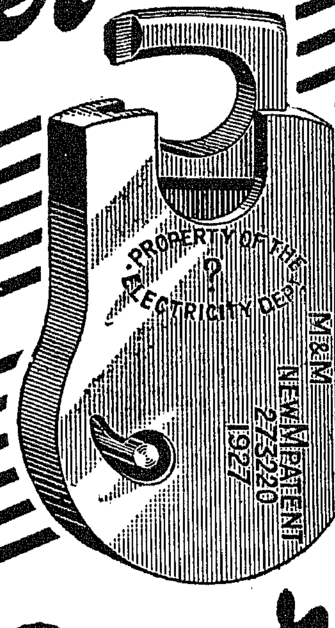

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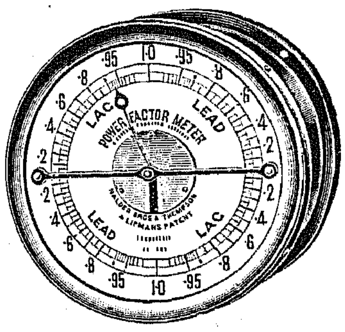

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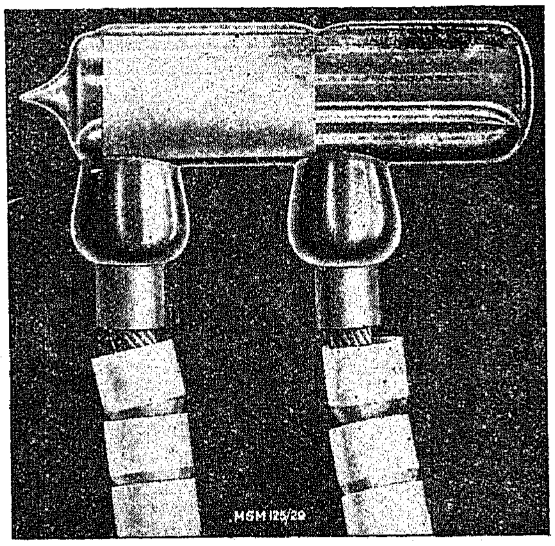

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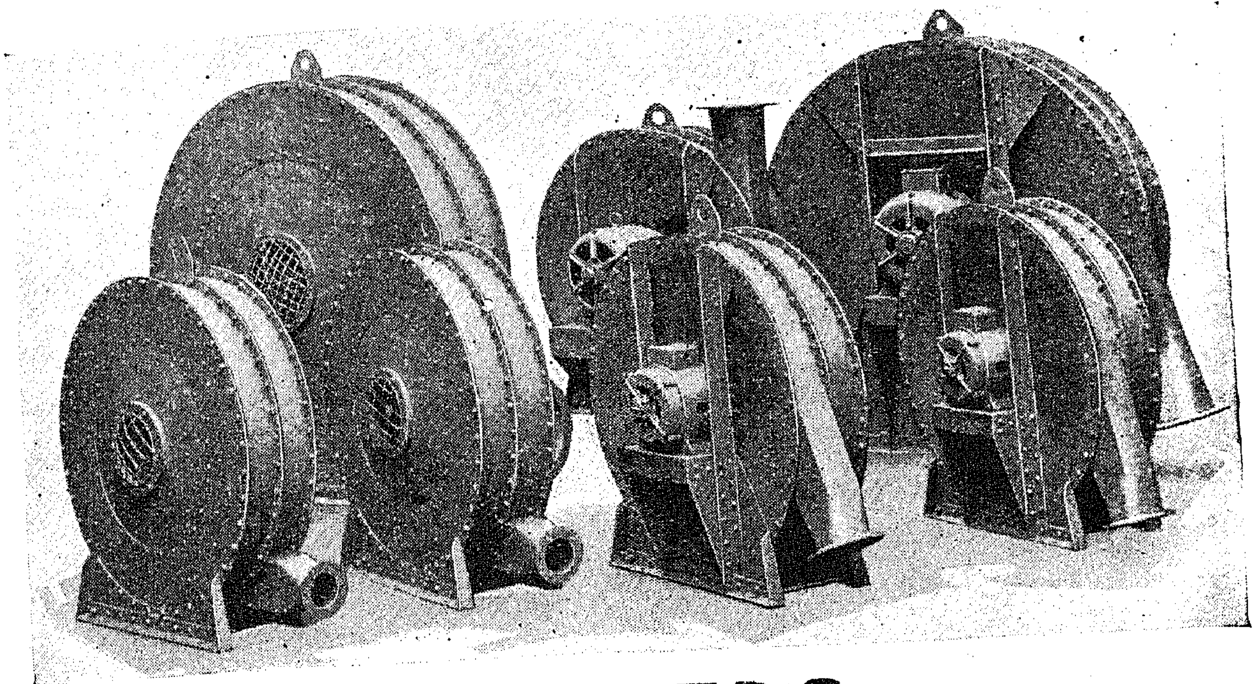

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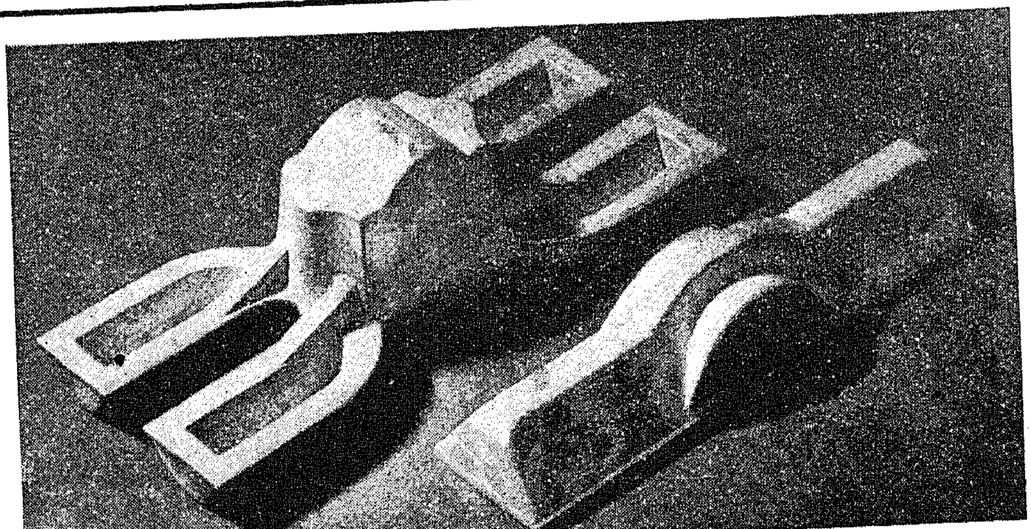

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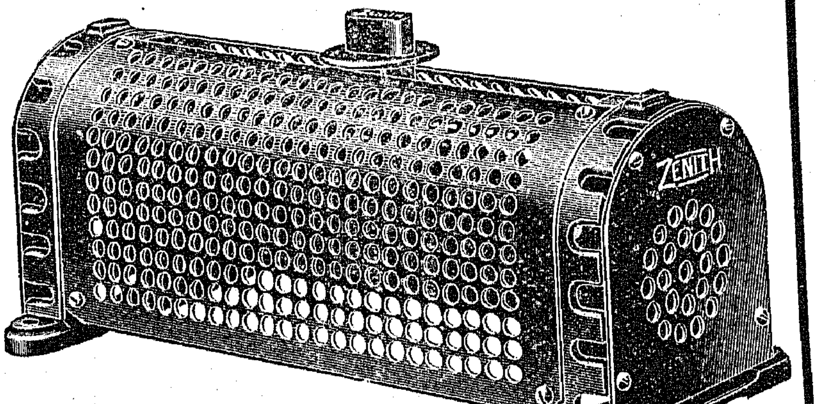

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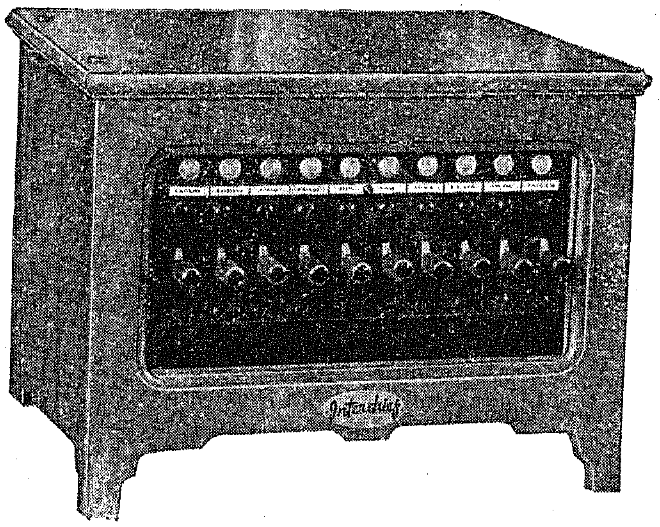

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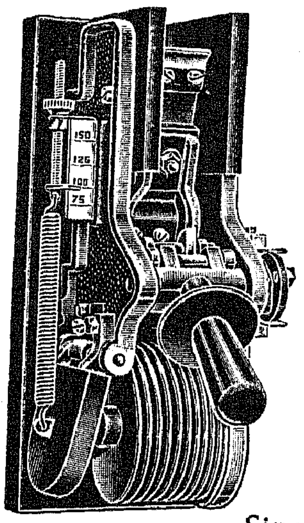

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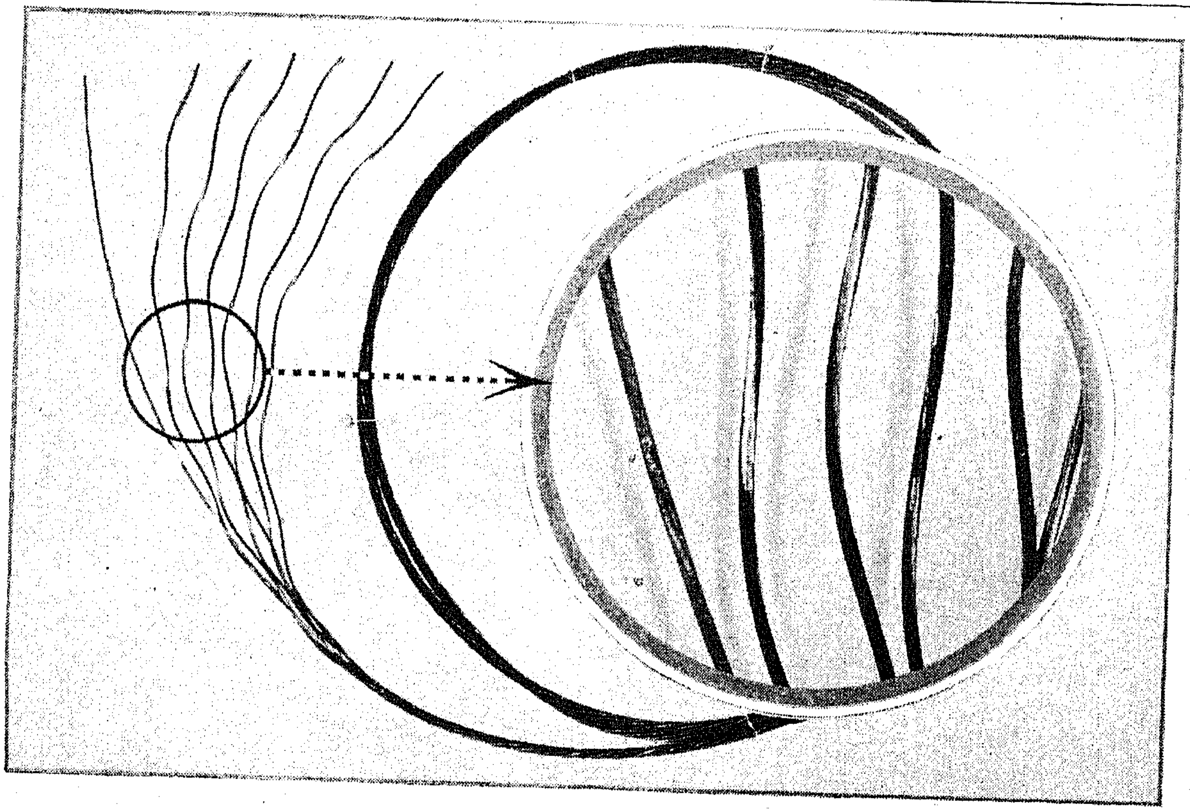

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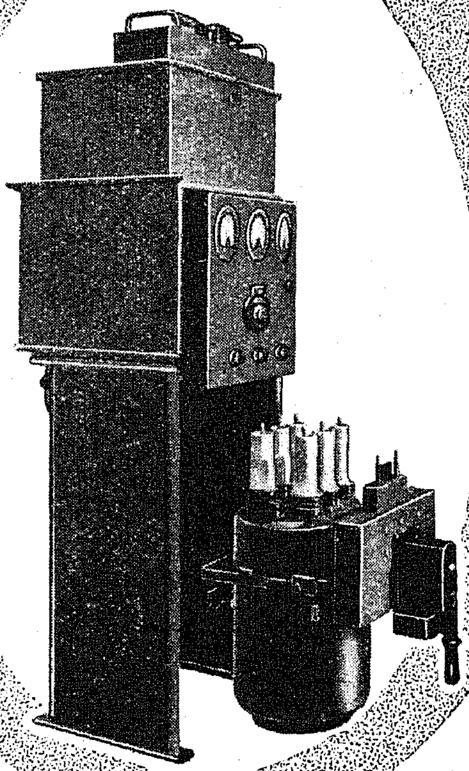

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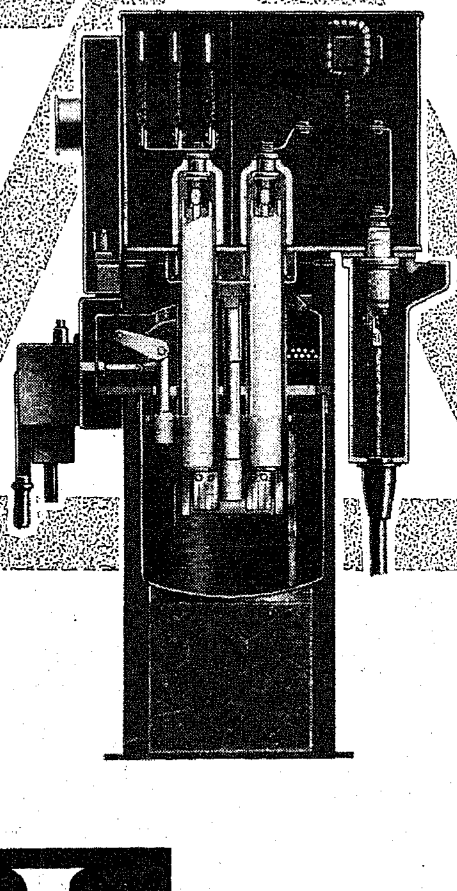

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